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A STUDY OF GEOMAGNETIC PULSATIONS USING THE AFGL MAGNETOMETER NETWORK

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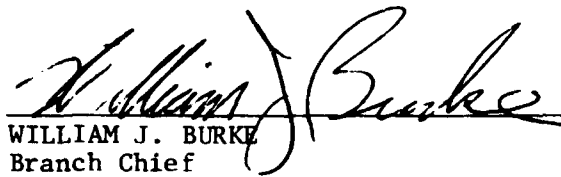HANSCOM AFB, MASSACHUSETTS 01731

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19. ABSTRACT (Continue on reverse if necessary and identify by block number) The objective of this work has been to study the midlatitude magnetic signatures of magnetospheric substorm onsets with the aim of using these signals to time and locate substorm onsets. The primary data source was the AFGL Magnetometer Network, a unique facility in that it spans over four hours in local magnetic time, a far greater extent than any other high-time-resolution network. Using this capability we have found that pi2 pulsation polarizations are ordered in longitude or local time. The direction of the major axis of the polarization ellipse varies with longitude, and points due north on the central meridian of the D.C. substorm current system. We have made use of this pattern to locate particular substorms. We have also shown that substorm onset signatures near geostationary orbit are far more localized than at midlatitudes on the ground. The geostationary orbit signature is usually localized to within the two meridians on which the main substorm field-aligned currents flow, whereas the ground signature is usually seen over the entire nightside of the earth. The latter we have shown by using data from Northern Europe in conjunction with the AFGL data. In addition to these studies, we have also made some theoretical contributions & participated in two data analysis workshops.

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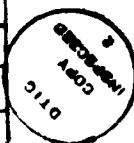
I. INTRODUCTION

The scientific objectives of this study were to better understand geomagnetic pulsations, especially those that accompany magnetospheric substorm onset (pi2 pulsations), making use of data from the AFGL Magnetometer Network. The ultimate goal of this research is to develop these pulsations as a useful indicator and monitor of magnetospheric activity, especially substorm and auroral activity.

The close association between pi2 pulsations and magnetospheric substorms has been recognized for a long time, and pi2's have been used to time substorm onsets for some time (Rostoker, 1968; Sakurai and Saito, 1976; Pytte et al., 1976). Indeed, in a consensus review, Rostoker et al. (1980) agreed that midlatitude pi2 pulsations provide the best method of timing substorm onsets. The study of pi2 pulsations has been hampered in the past by the lack of good quality data from arrays of magnetometers. Most of the networks that were built in the early 70's were latitudinal chains which provided good data to study the change in signal characteristics from the auroral zone to midlatitudes, but which were unable to provide local time coverage. The AFGL Network is unique in that it covers over four hours in magnetic local time at midlatitudes. Data from the Network have proved to be invaluable in helping to unravel the spatial structure of pi2 pulsations. With hindsight, we can see that the longitudinal pattern was beginning to emerge over ten years ago (Bjornsson et al., 1971) but it took the AFGL Network data to make this picture clear enough for us to be able to make use of our knowledge of this pattern to obtain the approximate position as well as the time of substorm onset.

The work performed under contract F19628-81-K-0003 can be split into several areas, each of which will be described in more detail in the next

section. In summary, the topics we have worked on are:

(A) Pi2 Pulsations and the Substorm Current System: Perhaps the most significant result arising from this contract is that pi2 wave characteristics, especially polarization characteristics, are better organized in longitude by the location of the substorm as determined by the midlatitude magnetic bays, than by local time. This not only provides an important key towards understanding the connection between pi2 pulsations and the substorm current system but also allows us to use pi2 pulsation characteristics to locate the region of substorm onset.

(B) Correlation of Substorm Signatures at Midlatitudes and Near Geostationary Orbit: Geostationary orbit and its vicinity is a very dynamic part of the magnetosphere. A substorm often dramatically changes the plasma environment and alters the geomagnetic topology in this region. Substorm onsets are accompanied by bursts of magnetic and electric oscillations. We have shown that these bursts are highly correlated with midlatitude pi2 pulsations. We have also found that the region of the magnetosphere affected by a substorm onset can be quite limited in local time at geostationary orbit although the midlatitude pi2 is seen over most of the nightside.

(C) Global Studies of Pi2 Pulsations: We have worked extensively with the IGS group in Scotland looking at the global characteristics of pi2 pulsations. This work was further aided by the 2nd AFGL Geomagnetism Workshop in which we played an active role. Pulsation signatures accompanying substorm onset are, at least at times, observed globally, that is at all local times. It is common for the pi2 signature to be seen over the entire nightside (i.e. > 12 hours in local time).

(D) Midlatitude Observations in Space: We have extensively studied one pi2

event which was observed both on the AFGL Network and by the ISEE 1 and 2 spacecraft which were magnetically conjugate to the Network at the time. There was a remarkable degree of correlation between the space and ground data. Using both electric and magnetic field data from ISEE 1 we were able to show that the wave had a standing structure along the field line and that the Poynting Vector had a net westward component.

(E) Theory: As well as working on an extensive review of the theory of hydromagnetic waves in the magnetosphere, Hughes, together with Dr. D.J. Southwood of Imperial College, worked on a theory of pi2 pulsations that would explain the spatial variations in wave characteristics we have been discovering. The non-uniform conductivity of the auroral ionosphere can play an important role in modifying any incident wave. We argue that this effect, together with partial reflection of a westward traveling incident wave, could explain the characteristics we observe.

(F) 2nd AFGL Geomagnetism Workshop: We played a very active role in the initial planning for, setting up, and running of the 2nd AFGL Geomagnetism Workshop and in the subsequent data analysis. The Workshop was organized as an interactive data analysis session bringing together about a dozen scientists from around the world and their various data sets. Extensive use was made of the AFGL computer system. Two topics were selected for particular study, pi2 pulsations and sudden impulses (si) and waves excited by si's.

(G) Co-ordinated Data Analysis Workshop (CDAW 6): We also took part in this large international effort whose overall goal is understanding energy transport and storage in the solar-terrestrial system. We have made use of the AFGL Network data to help locate substorm onsets during one of the intervals selected for study. The large amount of data collected for this interval also

allows us to test some of our ideas concerning the connection between pi2 pulsations and substorm current systems.

(H) Data Management and Analysis: A substantial part of the effort expended under this contract, especially that of our programmer, David Koonce, has been the setting up and maintenance of a suite of data management and analysis programs. There was very little software available to analyze the AFGL Network data when this contract began. It is largely through these efforts that we have been able to get as much done as we have. As a product, the contract leaves a suite of flexible data management and analysis software based on McPherron's (1976) block data set concept, which can be used on any time series data sets.

II. WORK COMPLETED

A. Pi2 Pulsations and the Substorm Current System

(References: Lester et al., 1983, 1984)

McPherron et al., (1973) introduced a simple current system illustrated in figure 1 to explain the magnetic signatures of a substorm. In this system, a portion of the dawn-to-dusk current flowing across the center of geomagnetic tail is diverted down field lines into the auroral ionosphere through which it flows as an enhanced westward electrojet. It then flows back along field lines to rejoin the tail current. This system is known as the substorm current wedge and although it is undoubtedly an over-simplification, it adequately models the midlatitude magnetic signatures of substorms seen, for example, by the AFGL Magnetometer Network. At midlatatudes the primary influence comes from the field-aligned portions of this current. The magnetic perturbations caused by these are illustrated in the upper part of figure 2 as a function of longitude or local time. The upward field-aligned current (FAC) causes an eastward perturbation, that is a positive perturbation in the geomagnetic D component, while the downward FAC causes a negative D perturbation, so the perturbation in D is antisymmetric about the central meridian of the current wedge, being positive to the west and negative to the east. The northwards, or H component perturbations are symmetric about the central meridian, being positive in the central region roughly corresponding to the region between the FAC meridians, and negative outside this region. The distance between the two FAC meridians varies, but is typically 60 – 90° of longitude or 4 – 6 hours in local time. On occasion it can be much narrower, say ~ 2 hours. The substorm currents and hence perturbations typically last for 30-60 min. The perturbations are known as magnetic bays.

We have made use of these signatures to order pi2 pulsation data. The bottom part of figure 2 shows schematically how the polarization of a pi2 pulsation varies with local time in relation to the magnetic bay signature. Each ellipse represents the variation of the wave associated magnetic perturbation vector with time in the horizontal plane. Everywhere the polarization is elliptical and rotates anticlockwise when looking downwards. However the direction of the major axis changes. It points north in the center of the pattern but east-west near the meridians of the field-aligned currents.

Our initial study concentrated on pi2 characteristics near the region where the D perturbation changes sign (Lester et al., 1983). Figure 3 shows the distribution of the magnetometer stations of the AFGL Network which we used in this study. The five northern stations span over four hours in magnetic local time. Of the 16 events selected as having the D perturbation change sign within the local time sector covered by the Network, 11 events fit the schematic pattern shown in figure 2 and 5 did not. Figure 4 illustrates two events that occured on 14 March 1978. This figure has the same form as figure 2, although it is drawn using real data. The vertical dashed lines indicate the central meridian of the substorm current wedge as determined by the D component perturbation, ΔD. The later event, shown on the right, fits the schematic pattern of figure 2, the earlier event on the left is one of the five events which did not. However, the direction of the major axes of the polarization ellipses does change in the expected manner but the central meridians of the ellipse pattern and bay pattern are different. This was true of all five events which did not fit the pattern as is shown in figure 5. In figure 5 the direction of the major axis of the polarization ellipse at each station for each event is plotted versus the difference in longitude between the station and the

center of the current wedge as determined from ΔD. Data from the 11 events are represented as dots which closely follow the dashed line which represents the variation expected for a model current system six hours wide and symmetric about the central meridian. Data from the five events are shown as crosses; points from the same event have been joined by straight lines. Looked at individually, the points from each event form a line with a similar average slope to the dashed line, but displaced from the dashed line. This means that the variation in polarization direction follows the expected pattern, but with the center of the pattern displaced from the center defined as where ΔD = 0.

Investigating these five events further we found that they all occured during an already disturbed interval. Since we defined the bay structure by simply the slope of the background field during the pi2 interval, preexisting current systems which were also changing with time during the event would bias the results. In our subsequent study (Lester et al., 1984) we selected only events which followed intervals of quiet and these showed much better agreement.

Figure 6 shows schematically the polarizations of the 25 events studied by Lester et al. (1984). In this study the H component bay signatures were also used to define the location of the substorm current system. This allowed us to extend our study outside the meridians of the field-aligned currents. Within the two meridians defined by ΔH = 0, there are only two events which significantly differ from the figure 2 schematic. These are, counting from the top, the thirteenth and twenty-first events. The twenty-first event has clockwise polarization throughout, indicated by shaded ellipses. The thirteenth event has the center of the polarization pattern significantly removed from the ΔD = 0 meridian. Outside the region of the current wedge, there are more exceptions to the pattern, for example the incidence of clockwise polarization

increases. Nevertheless the pattern continues. Figure 7 illustrates the variation in ellipse orientation more quantitatively. Ellipse orientations are plotted versus the longitude of the station away from one of the three meridians defined by $\Delta H = 0$ or $\Delta D = 0$. Remembering that there is a 180° ambiguity to ellipse orientation, so that 0° and 180° are equivalent, a general trend of points from the lower left to upper right of the figure appears. The thirteenth event contributed four of the wayward points in the center of the diagram. If this one event is removed the pattern is even more clear. Increasing scatter towards the edges of the figure is evident.

As well as pi2 polarization characteristics, we calculated signal phase differences between stations. This allows us to compute an apparent east-west wave number. Figure 8 shows the results of this study. The angular wave number, m, obtained from phase differences in the D component is plotted versus the longitude of the midpoint between the two stations relative to one of the meridians defined by $\Delta H = 0$ or $\Delta D = 0$. Only adjacent pairs in the chain of five northern stations were used. Error bars are drawn whenever they cross the $m = 0$ axis and are representative of the errors on all the points. The significant result is that in the center and west of the current system the wave numbers are predominantly negative meaning westward apparent phase propagation while east of the current system most of the values are positive. The significance of this result is discussed in section E on theory.

What this aspect of our work has shown is that the properties of pi2 pulsations, in particular their polarization, is best ordered in longitude by a system based on the magnetic perturbations caused by the DC currents of the substorm with which the pi2 is associated. This means that the pi2 can be used to help locate where a particular substorm is occuring. If the interval is at

all magnetically active, this method is probably better than a method based on the midlatitude bay structure itself.

B. Correlation of Substorm Signatures at Midlatitudes and near Geostationary Orbit

(References: Singer et al., 1983a,b)

We have examined the correlations between pi2 signatures seen on the AFGL Magnetometer Network with signatures seen near geostationary orbit using primarily magnetometer data from the NOAA GOES series of spacecraft, but also some SCATHA spacecraft data. Figure 3 shows the relationship of the AFGL Magnetometer Network Stations to the magnetic conjugate points of GOES 2 and 3 during the interval we have studied. Our initial study (Singer et al., 1983a) showed that substorm onset signatures are more localized in local time at geostationary orbit than they are on the ground. Figure 9 shows two examples of pi2 wave bursts, one seen by GOES 2 but not by GOES 3 and the other by GOES 3 but not by GOES 2. In both cases a pi2 pulsation was seen by all the AFGL stations which were operating. Inspection of figure 3 shows that the AFGL stations span a greater extent in local time (~ 4 hours) than do the spacecraft (~ 2 1/2 hours). Moreover, the event seen by GOES 3 (figure 3) is seen over the entire Network even though parts of it are east of GOES 2, which sees no signature.

Another result we obtained is that during relatively quiet geomagnetic conditions (Kp $\leq$ 2+) there is a greater likelyhood of detecting a pi2 on the ground than a wave burst in space, and that this likelyhood increases with decreasing Kp. However during more disturbed times (Kp $\geq$ 3-) there is roughly equal probability of seeing a wave at both locations. This is illustrated in

Figure 10. Figure 11 illustrates a possible explanation of this result. During

quiet times the auroral oval contracts (e.g. Gussenhoven et al., 1981). If pi2

pulsations originate on field lines which map down to the auroral oval as seems

to be the case (e.g. Saito et al., 1976; Samson, 1982) then the source region

of pi2 pulsations would be substantially tailward of geostationary orbit during

quiet times. During active times, when the auroral oval is expanded, stationary

spacecraft are more likely to be close to auroral zone field lines. Indeed,

during very disturbed times geostationary spacecraft have been known to exit the

plasmasheet and enter the tail lobe.

In subsequent work (Singer et al., 1983b) we have examined how the signal

in space is related to the position of the DC substorm current wedge (McPherron

et al., 1973) described in the last section. Here we illustrate the effect

using as an example a pi2 pulsation which occured on 16 July 1979. Figure 12

shows H and D component data from the AFGL Magnetometer Network. Both a

geomagnetic bay and a pi2 pulsation begin abruptly at 0728 UT. The H component

bay is positive at all stations but the D component bay changes sign, being

positive at the western stations (LOC, RPC) and negative at the eastern stations

(MCL, SUB, TPA). The D component bay at CDS at 0727 UT is very small but

negative which means that the central meridian of this substorm is just west of

the CDS meridian. The polarization of the pi2 pulsation is shown using

hodograms in Figure 13. The wave polarization pattern confirms the conclusions

reached from the bay structure; the Network spans the region between the two FAC

meridians with the central meridian just west of CDS. We now turn to the

spacecraft data. The GOES 2 meridian passes between CDS and RPC, so we predict

that GOES 2 is very close to the central meridian of the substorm; GOES 3 on the

other hand is west of NEW and LOC, so at the edge of or outside the current

wedge (cf. figure 3). Figure 14 shows the GOES 2 and 3 data. GOES 2, near the center of the substorm, sees a burst of wave noise and a field reconfiguration beginning at 0727 UT. The field direction changes to a more dipolar one. GOES 3 sees nothing unusual at 0727 UT. About five minutes later, the field at GOES 3 becomes a little more tail like, perhaps due to an increase in the ring current population which was injected by the substorm.

An initial statistical study confirms the result obtained from this one example. Geostationary spacecraft see a large burst of wave noise at substorm onset only if they are near the central meridian of the substorm current system.

C. Global Studies of Pi2 Pulsations

(References: Singer et al., 1981, 1982)

We have collaborated extensively with W.F. Stuart and C.A. Green of the Institute of Geological Sciences (IGS) in Edinburgh. By using both the IGS Magnetometer Network (located primarily in the U.K. and Scandinavia) and the AFGL Network we have studied pi2 signatures far from the local time of substorm onset. By combining the networks we obtain a total coverage of over 10 hours in local magnetic time.

Figure 15 shows an example of a pi2 pulsation which occured when the IGS Network was near local midnight. Both the pi2 pulsation and the associated bay are clear in the IGS data in the upper part of the figure. Both start at 2333 UT. Simultaneously a small amplitude wave was seen on the AFGL Network, as is shown in the lower part of the figure. Spectral analysis of this data showed that power enhancements occured at the same frequency at all stations, but that the power was as much as 25 times greater at midnight (IGS) than near dusk (AFGL).

An investigation of eight events indicated that good pi2 waveforms are primarily observed between dusk and dawn on the nightside, but waves associated with pi2's can be observed on the dayside. The propagation time is difficult to measure because the onset of the waves is often not sharply defined; however, delays even as small as ~ 10 s are not inconsistent with a magnetospheric propagation path at Alfven velocities.

We found that the AFGL Network has ideal instrumentation and is in a good location to observe pi2 pulsations and hence detect substorm activity on the dayside of the earth. However, more work is needed to be able to use these observations as substorm diagnostics because the pi2's can be difficult to distinguish from other dayside oscillations. We found that the pi2 waveform has a different character between dayside and nightside, but that the period of the pulsations can be the same across many hours of local time.

D. Midlatitude Observations in Space

(Reference: Hughes et al., 1981)

The burst of wave noise typically observed at geostationary orbit at substorm onset is quite unlike the classical midlatitude ground pi2 pulsation. Correlating wave observations made on the ground and in space using spacecraft other than geostationary or near-geostationary orbiting satellites is very difficult, primarily because other spacecraft move too fast when they are in interesting regions of the magnetosphere. However we have studied extensively one pi2 pulsation which occured when the ISEE 1 and ISEE 2 spacecraft were inbound and on field lines which intersect the earth's surface just north of the center of the AFGL Network. Figure 16 shows the magnetic event is of extreme interest as it is the first good pi2 observation made in space significantly

inside geostationary orbit. We found that the wave forms seen in space and on the ground were remarkably similar (figure 17) in marked contrast to what is normally seen further out in the magnetosphere. Figure 18 shows hodograms made with the AFGL Network data. These tell us that the central meridian of the substorm was roughly due north of SUB. This is confirmed by the Great Whale River (GWR) magnetogram and the GOES 2 data. So ISEE 1 and 2 were near the center of the disturbance. As shown in figure 17 we had both magnetic and electric field data available from ISEE 1, and thus were able to compute the wave Poynting vector. This is shown in figure 19. The field-aligned component, S_z, oscillates with twice the wave frequency about a mean value which is slightly negative. The amplitude of the oscillations is several times larger than the mean value. This means that along the field line the signal has primarily a standing structure, but that there is some net flow of electromagnetic energy which is directed southwards, towards the ionosphere nearer to the spacecraft, where presumably it is being dissipated by Joule heating. This observation conclusively shows that midlatitude pi2 pulsations are standing waves (but not necessarily resonant ones). The two perpendicular components, S_x and S_y, oscillate at twice the wave frequency, but in this case the oscillations are about a larger mean value. Energy is propagating westward away from midnight, in the same sense as the normal apparent phase velocity of pi2 pulsations observed on the ground. The direction of the perpendicular component of the Poynting vector is shown in figure 20 which also shows the positions of the various observatories in L – MLT space.

E. Theory

(References: Southwood and Hughes, 1983, 1984)

The observations described in the previous sections place constraints on any theory of pi2 pulsations. Working under the assumption that pi2 pulsations can be described using MHD theory, we have investigated what these constraints imply. We began our study by asking what effect the ionospheric auroral conductivity enhancement has on an Alfvenic signal propagating along field lines down to the ionosphere. Earlier work (Ellis and Southwood, 1983) had shown that, except in certain special cases, subsidiary waves are set up on field lines which intersect the ionosphere along a line across which there is a change in ionospheric conductivity. The conductivity of the nightside auroral zone ionosphere is typically an order of magnitude or more larger than that of the surrounding ionosphere. In effect there is an east-west aligned high conductivity strip, perhaps a couple of degrees of latitude wide, resulting from the ionization caused by the precipitating auroral particles.

Extending the work of Ellis and Southwood, we calculated what the effect of such a conductivity strip would be. We assumed that the incident Alfven wave was linearly polarized in the east-west direction, i.e. along the direction of the strip, as this is consistent with an earthward flow of plasma in the magnetosphere. The resulting ionospheric electric fields are shown in figure 21. In computing these fields we assumed that the conductivity outside the strip was very small. The three panels correspond to different Hall and Pedersen conductivity ratios within the strip. The electric field vectors are drawn as arrows. The dashed lines represent Hall current flow, which is non-divergent within the strip, but which does help feed field-aligned currents that flow along the field lines which intersect the ionosphere along the edges

of the strip.

In the central panel of figure 21, the integrated Hall conductivity is five times the integrated Pedersen conductivity, which is typical of the nightside auroral zone. Field-aligned current flows both out of the middle of the strip, from the regions from which the electric field diverges, and from along the strip edges. These latter field aligned currents are those associated with the subsidary waves resulting from the conductivity boundaries. These subsidary waves are circularly polarized. As the incident and regular reflected waves are both linearly polarized in the east-west direction, the all north-south components of the electric field in figure 21 are due to the subsidiary waves induced on the two strip edges. In the top panel the subsidiary wave electric fields totally cancel the incident electric fields at the strip boundaries. In all cases the field direction and amplitude is considerably altered by the presence of these subsidiary waves.

The other aspect of the problem we looked at was the polarization pattern we had found observationally. In the model just described in which the incident wave is a simple traveling wave, wave polarization is independent of longitude. As described earlier, pi2 polarizations change systematically with longitude. This might imply that pi2 signals have a standing structure in the east-west direction (as well as along the fieldline). However, this also cannot be so for two reasons. Pi2 signals have finite east-west phase differences and are in general elliptically polarized while a pure standing wave would necessarily be linearly polarized and be in phase (or 180° out of phase) at all points. Thus pi2 signals cannot have either a pure standing or pure traveling wave structure in the east-west direction.

Figure 22 is a schematic diagram illustrating how the observed pi2

polarization pattern could be produced. The top two rows of circles represent

observations made using an east-west chain of seven equispaced observatories of

two circularly polarized waves, a westward traveling, anticlockwise polarized

wave and an eastward traveling, clockwise polarized wave of half the amplitude

of the first wave. The wave perturbation vectors observed at the different

places at the same time are shown as a solid line. The perturbations 1/4 of a

cycle later are shown as dashed lines. Linear superposition of these two waves

results in the line of ellipse along the bottom of the figure which is very

similar to the observations of pi2 polarizations presented earlier (e.g.

figures 6, 13 and 18). This composite wave also has a net westward apparent

phase velocity which is consistent with our and other observations (figure 7).

Although this is far from a complete theory of pi2 pulsations and much work

needs to be done before we fully understand these signals, we have illustrated

the importance of the auroral ionosphere conductivity structure in determining

signal characteristics. Moreover we have shown that the superposition of two

relatively simple waves, such as might result from the reflection of an incident

westward-traveling wave off some boundary to the west of the system, does

produce a polarization structure similar to that we observe.

F. 2nd AFGL Geomagnetism Workshop

(References: Fougere et al., 1982; Singer et al., 1982; Hughes et al.,
1982)

The second AFGL geomagnetism workshop was held on December 2-4, 1981. The

meeting was formatted as a data analysis workshop and organized by Drs. Paul

Fougere (AFGL) and Howard Singer (BU). Data from more than 80 ground based

magnetometers from nine different networks were collected and merged into one

large computer-based data base. Fourteen scientists attended the workshop which studied the impulse response of the magnetosphere. Two types of phenomena were selected to do this: sudden impulses (si) which occur when interplanetary shock waves suddenly compress the magnetosphere, and the irregular pulsations (pi2) which occur at magnetospheric substorm onset.

A suite of interactive data analysis programs was available for use at the workshop. These had been developed by Bedford Research Associates and by David Koonce (BU). It was only possible to do a very preliminary analysis of the data at the workshop, however the two working groups, one studying each phenomenon, did outline a program of initial analysis. This program was begun after the workshop with Dr. Singer analyzing the pi2 events and Prof. Hughes the si events. Initial results from this study were presented at the Fall AGU meeting in December 1982. These initial papers were circulated around the workshop participants and further suggestions received back. The final papers are in the final stages of preparation.

The pi2 study has confirmed that, at least for some events, there is a global enhancement of wave power in the pi2 frequency band at the time a pi2 pulsation occurs near local midnight. Wave power decreases systematically with both latitude and distance from the midnight meridian. The frequency at which wave power is most enhanced also varies.

The si study showed that these impulses propagate so rapidly that time delays between stations are of the same order as the timing accuracy, 10-20 s. The rise time of the initial impulse varies systematically with position, becoming longer away from noon and towards lower latitudes. The polarization of the main impulse changes direction between high and low latitudes. This change occurs between 65-70° latitude. A wide spectrum of pulsations was excited by

some of the si's studied. The frequency of these waves varied by as much as a factor of 20 from high to low latitudes, and there were definite localized regions within which a narrow band of frequencies dominated. Some of these regions had the polarization properties of field line resonances. Within other regions small changes of frequency with latitude could be detected.

G. Coordinated Data Analysis Workshop, CDAW 6

Professor Hughes has been actively participating in and leading the wave subgroup of CDAW 6, a large international collaborative effort to help understand the processes of energy transport within the solar-terrestrial system. The workshop has concentrated on analyzing two large data bases covering two several-hour-long time periods chosen as being good examples of geomagnetically active intervals which occured when the several spacecraft of the IMS were advantageously placed. One of these intervals (22 March 1979) occured when the AFGL Network was near local midnight and a series of substorm onsets was observed as pi2 pulsations and bays. We have used these midlatitude signatures to help time and locate the substorm onsets which occured during this interval. This information is particularly useful for the other participants in the workshop working with other data sets. We are also using this unique data suite to test some of our own ideas. In particular, the large number of magnetic records collected for these intervals has enabled Kamide et al. (1983) (see also Kamide and Baumjohann, 1984) to predict the global ionospheric and field aligned current systems more accurately than has ever been done before. We are making use of these predictions to test our models of the pi2 polarization patterns described earlier.

H. Data Management and Analysis

In an attempt to make our analysis of the AFGL Magnetometer Network data and other data sets more efficient, we created a suite of data management and analysis software on the AFGL CDC computer. The creation and maintenance of this software was a substantial part of our programmer's effort.

We used the concept of Block Data Sets (McPherron, 1976) in which time series data is stored in a standardized format. Data sets are self-documenting in that an initial data record completely describes the data contained in the set, such as number of dependent parameters, digitization interval and so on. By storing all data in this format, we could then write one set of analysis software which operated on data sets of this type. Our analysis software now includes programs to edit data sets, plot data sets, filter data in the time domain, Fourier-transform data sets and calculate power spectra or cross spectra and so on. These analysis programs are quite general and can be used on any time series data which has been written in a block data set form. They remain on the AFGL Computer system as a product of this contract.

III. BUSINESS DATA

A. Contributing Scientists

Boston University

      R.A. Daly, Graduate Student

      C.G. Gelpi, Research Associate

      W.J. Hughes, Assistant Professor

      G.J. LaQuadra, Graduate Student

      M. Lester, Research Associate

      H.W. Rhodehamel, Graduate Student

      H.J. Singer, Research Assistant Professor (until 30 June 1982)

AFGL

      P.F. Fougere

      D.J. Knecht

      H.J. Singer (since 1 July 1982)

Other

      W. Baumjohann (U. Münster, FRG)

      C.A. Green (Institute of Geological Sciences, U.K.)

      L.J. Lanzerotti (Bell Laboratories)

      C.G. Maclennan (Bell Laboratories)

      N.C. Maynard (NASA/Goddard SFC)

      J.C. Samson (U. Alberta, Canada)

      D.J. Southwood (Imperial College, U.K.)

      W.F. Stuart (Institute of Geological Sciences, U.K.)

B. <u>Previous</u> <u>and</u> <u>Related</u> <u>Contracts</u>

F19628-80-C-0025   (12.15.79 - 11.30.80)

F19628-84-K-0006   (12.1.83 - 9.30.86)

C. <u>Publications</u>

i. <u>Published</u> <u>Papers</u>

Hughes, W.J., Pulsation Research during the I.M.S. Rev. Geophys. Space Phys., <u>20</u>, 641, 1982.

Singer, H.J., Multisatellite Observations of resonant hydromagnetic waves. Planet. Space Sci., <u>30</u> 1209, 1982.

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Singer, B.J., Hughes, W.J., Fougere, P.F. and Knecht, D.J., The localization of pi2 pulsations: Ground satellite observations. J. Geophys. Res., <u>88</u>, 7029, 1983.

Lester, M., Hughes, W.J., and Singer, H.J., Polarization patterns of pi2 magnetic pulsations and the substorm current wedge. J. Geophys. Res., <u>88</u>, 7958, 1983.

Southwood, D.J. and Hughes, W.J., Theory of hydromagnetic waves in the magnetosphere. Space Sci. Rev., <u>35</u>, 301, 1983.

Hughes, W.J., Hydromagnetic waves in the magnetosphere. Rev. Geophys. Space Phys., <u>21</u>, 508, 1983.

Southwood, D.J. and Hughes, W.J., Concerning the structure of pi2 pulsations. J. Geophys. Res. (in press) 1984.

Lester, M., Hughes, W.J. and Singer, H.J., Longitudinal structure in pi2 pulsations and the substorm current wedge. J. Geophys. Res. (submitted).

ii. Papers in Preparation

Hughes, W.J., Singer, H.J., and Maynard, N.C., Midlatitude pi2 pulsations: ISEE and AFGL magnetometer observations correlated.

Hughes, W.J., Singer, H.J., Fougere, P.F., Baumjohann, W., and Lanzerotti, L.J., Global observations of si's and si excited waves.

Singer, H.J., Hughes, W.J., Fougere, P.F., et al., Global observations of pi2 pulsations.

Singer, H.J., and Hughes, W.J., Synchronous satellite magnetic disturbances and the substorm current wedge.

iii. Papers Presented at Meetings

Singer, H.J., Hughes, W.J., Fougere, P.F., and Knecht, D.J., Pi2 pulsations observed in space and on the ground. Fall AGU meeting, San Francisco, Dec. 1980. (Abstract: EOS, 61, 1086, 1980).

Hughes, W.J., Pulsation research during the IMS. Invited Review Paper, International Magnetospheric Study Assessment Symposium. NASA/Goddard Space Flight Center, May 1981.

Hughes, W.J., and Singer, H.J., Polarization patterns and current patterns associated with a pulsation resonance region. Spring AGU meeting, Baltimore, May 1981. (Abstract: EOS, 62, 357, 1981).

Knecht, D.J., and Singer, H.J., Multistation observations of simultaneous pi 1 and 2 pulsations at substorm onsets. Spring AGU meeting, Baltimore, May 1981. (Abstract: EOS, 62, 358, 1981).

Hughes, W.J., The magnetosphere: a natural plasma laboratory, Invited Lecture at South African Institute of Physics Annual Conference, Port Elizabeth, July, 1981.

Hughes, W.J., Ground-satellite correlations of Pi 2 pulsations, SAIP Annual Conference, Port Elizabeth, July 1981.

Hughes, W.J., Field-aligned currents, magnetospheric convection and the source of impulsive pulsations, SAIP Annual Conference, Port Elizabeth, July 1981.

Hughes, W.J., and Singer, H.J., The currents and wave polarizations associated with a pulsation resonance region. IAGA Scientific Assembly, Edinburgh, August 1981.

Singer, H.J., Hughes, W.J., Fougere, P.F., Knecht, D.J., and Stuart, W.F., Pi 2 pulsations at midlatitude ground networks and geostationary orbit. IAGA Scientific Assembly, Edinburgh, August 1981.

Hughes, W.J., Singer, H.J., Maynard, N.C., Midlatitude Pi 2 pulsations: ISEE and AFGL magnetometer observations correlated. Fall AGU meeting, San

Francisco, December 1981. (Abstract: EOS, 62, 1014, 1981).

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XXIV COSPAR, Ottawa, May 1982.

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determined from ISEE, Synchronous Satellite and AFGL Magnetometer Network
observations, STP Symposium, XXIV COSPAR, Ottawa, May 1982.

Hughes, W.J., Hydromagnetic waves in the magnetosphere: Two Invited Lectures,
Summer School on Theory of Solar-Terrestrial Physics, Boston College,
August 1982.

Hughes, W.J., Singer, H.J., et al., AFGL geomagnetism workshop -- global
observations of si's and si excited waves. Fall AGU meeting, San
Francisco, December 1982. (Abstract: EOS, 63, 1063, 1982).

Singer, H.J., Hughes, W.J., et al., AFGL geomagnetism workshop -- global
observations of Pi 2 pulsations. Fall AGU meeting, San Francisco, December
1982. (Abstract: EOS, 63, 1063, 1982).

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pulsations on a mid-latitude east-west magnetometer chain. Fall AGU
meeting, San Francisco, December 1982. (Abstract: EOS 63, 1077, 1982).

Hughes, W.J., MHD waves in the magnetosphere. Invited Review, MIT symposium on
"Physics of Space Plasmas." January 1983.

Hughes, W.J., Pi 2 pulsations and the substorm current system. Invited Paper,
Royal Astronomical Society MIST Meeting, Keele, April 1983.

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Pi 2 current systems. Spring AGU meeting, Baltimore, May 1983. (Abstract:
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Hughes, W.J., Singer, H.J., and Lester, M., Pi 2 pulsations and the substorm
current system. IUGG XVII General Assembly, Hamburg, August 1983.

Singer, H.J., Hughes, W.J., Fougere, P.F., and Knecht, D., Global observations
of Pi 2 pulsations. IUGG XVII General Assembly, Hamburg, August, 1983.

D. Travel Undertaken and Meetings Attended

All the trips listed below involved contract research. However many of the trips combined other business so that only a fraction of the travel costs were borne by the contract.

Prof. Hughes and Dr. Singer attended the Fall AGU meeting in San Francisco in December 1980 and presented papers describing contract supported research.

Dr. Singer visited Dr. J.C. Samson at University of Alberta for one week in April 1981 to discuss collaborative research projects, models of pi2 current systems and Dr. Samson's analysis techniques.

Prof. Hughes and Dr. Singer attended the IMS Assessment Symposium at Goddard SFC in May 1981 where Prof. Hughes presented an invited review paper.

Prof. Hughes and Dr. Singer attended the Spring AGU meeting in Baltimore in May 1981 and presented a paper describing contract funded research.

Dr. W.F. Stuart (UKIGS) visited Boston for four days in late May 1981. The purpose of this visit was to further the collaboration between his magnetometer network and the AFGL Network. His local travel expenses were paid from the contract.

Prof. Hughes and Dr. Singer attended the 4th IAGA Scientific Assembly held in Edinburgh in August 1981. A paper describing contract related research was presented. The costs of attending this meeting were funded from other sources.

Dr. Singer visited Drs. Stuart and Green in Edinburgh for a week in August 1981 during which they analyzed and discussed pi2 events seen on both magnetometer networks.

Dr. W.F. Stuart (UKIGS) spent 10 days prior to the 2nd AFGL Geomagnetism Workshop in December 1981 in Boston in order to further our collaboration. His local expenses were paid by the contract.

Prof. Hughes and Dr. Singer attended the 2nd AFGL Geomagnetism Workshop in December 1981 at no cost to the contract. Prof. J.V. Olson's airfare from Alaska to Boston in order to attend the Workshop was paid from the contract.

Prof. Hughes attended CDAW 6.0 (Co-ordinated Data Analysis Workshop) in Palo Alto in December 1981.

Prof. Hughes and Dr. Singer attended the Fall AGU meeting in San Francisco in December 1981 and both presented papers describing contract supported research.

Dr. Singer visited UCLA to discuss AFGL-ISEE collaboration and data management and analysis techniques in December 1981, immediately following the AGU meeting.

Prof. Hughes attended the CDAW 6.1 workshop at Goddard SFC in February 1982.

Prof. Hughes and Dr. Singer attended the XXIV COSPAR Assembly in Ottawa in May 1982 and both presented papers.

Dr. Lester's moving expenses from York, England to Boston in order to take up his appointment at Boston University in July 1982 were partially paid from contract funds.

Dr. Lester and Prof. Hughes attended the Solar-Terrestrial Theory Institute held at Boston College, August 1982. Prof. Hughes presented two tutorial lectures.

Prof. Hughes attended the CDAW 6.3 workshop held at Goddard SFC in October 1982.

Prof. Hughes and Dr. Lester attended the Fall AGU meeting in San Francisco in December 1982, where they both presented papers describing contract related research.

Prof. Hughes attended the Chapman Conference on Waves in Magnetospheric Plasmas in Hawaii in February 1983. None of his expenses were charged to the contract.

Prof. Hughes spent five weeks at Imperial College, London in March/April 1983. This visit was at Imperial College's invitation and they paid travel expenses. During this visit he worked with Dr. D.J. Southwood on a theory of pi2 pulsations. He also visited Dr. W.F. Stuart in Edinburgh for two days in order to discuss future collaboration. Travel from London to Edinburgh was charged to the contract.

Dr. Lester attended the sixth European IMS workshop in Windsor, England in May 1983 where he began several collaborative projects with European groups.

Prof. Hughes and Dr. Lester attended the Spring AGU meeting in Baltimore in May 1983 where Dr. Lester presented a paper describing contract related research.

Prof. Hughes attended the IUGG XVIII General Assembly in Hamburg, FRG in August 1983. He presented a paper which reviewed work done under the contract during the last three years. None of his expenses was charged to the contract.

E. Cumulative Cost and Fiscal Information

	Amount Planned	Amount Spent
Salaries		
Principal Investigator	30,970	31,172
Research Associates	68,850	70,210
Applications Programmer	43,000	46,076
Other Staff and Students	24,900	7,626
Total Salaries	165,720	155,084
Other Direct Expenses		
Fringe Benefits	28,425	28,141
Foreign Travel	3,600	5,705
Domestic Travel	6,300	8,734
Computing	2,700	5,961
Other Expenses	9,200	8,620
Equipment	0	5,049
Total Direct Expenses	215,945	217,294
Indirect Expenses (overhead)	86,755	85,406
TOTAL	302,700	302,700

All of the $302,700 allocated to the contract has been spent. The work has been completed.

IV. REFERENCES

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Gussenhoven, M.S., Hardy, D.A., and Burke, W.J., DMSP/F2 electron observations of equatorward auroral boundaries and their relationship to magnetospheric electric fields. J. Geophys. Res., 86, 768, 1981.

Hughes, W.J., Singer, H.J., and Maynard, N.C., Midlatitude pi2 pulsations: ISEE and AFGL magnetometer observations correlated. EOS, 62, 1014 (abstract only), 1981.

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Rostoker, G., Macrostructure of geomagnetic bays, J. Geophys. Res., 73, 4217, 1968.

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Southwood, D.J., and Hughes, W.J., Concerning the structure of pi2 pulsations. J. Geophys. Res., (in press), 1984.

V. FIGURES
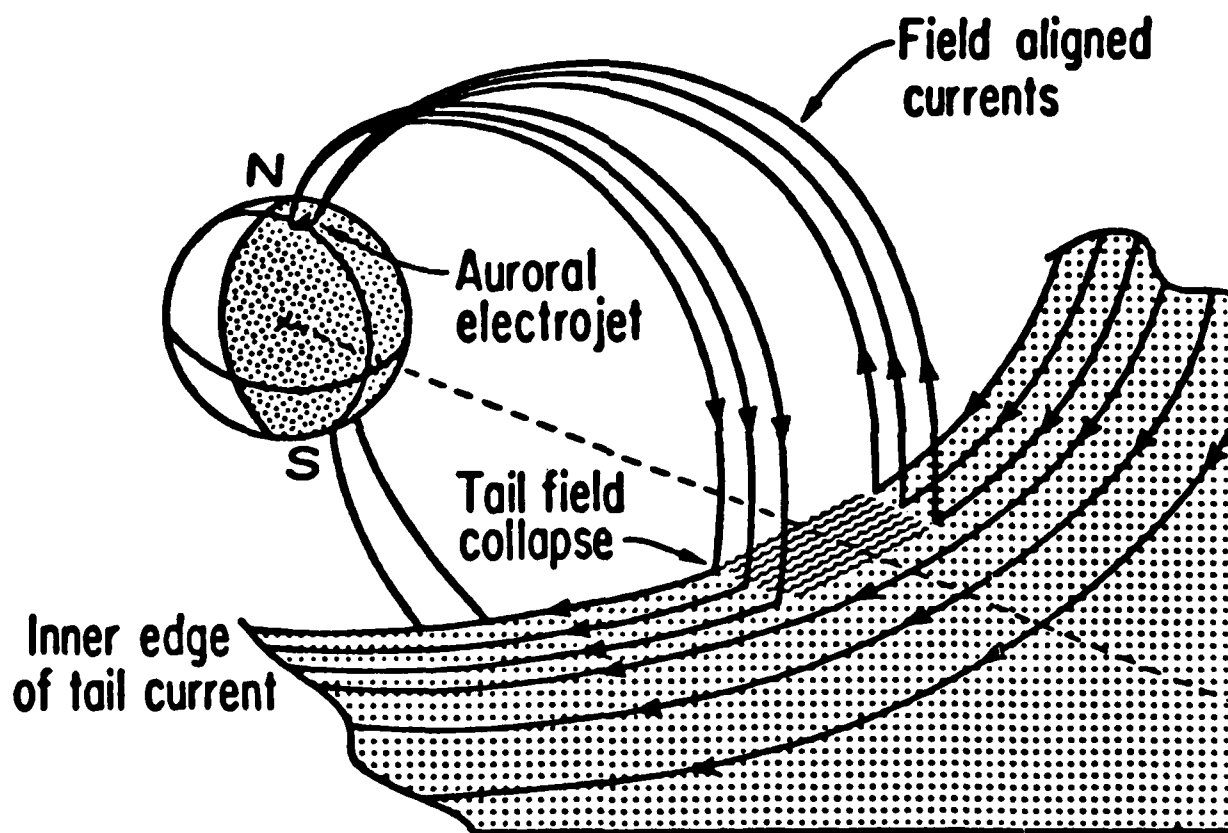
Figure 1: The substorm current system introduced by McPherron et al., (1973). Part of the cross-tail current is diverted down field lines and closes via a westward electrojet in the auroral ionosphere.
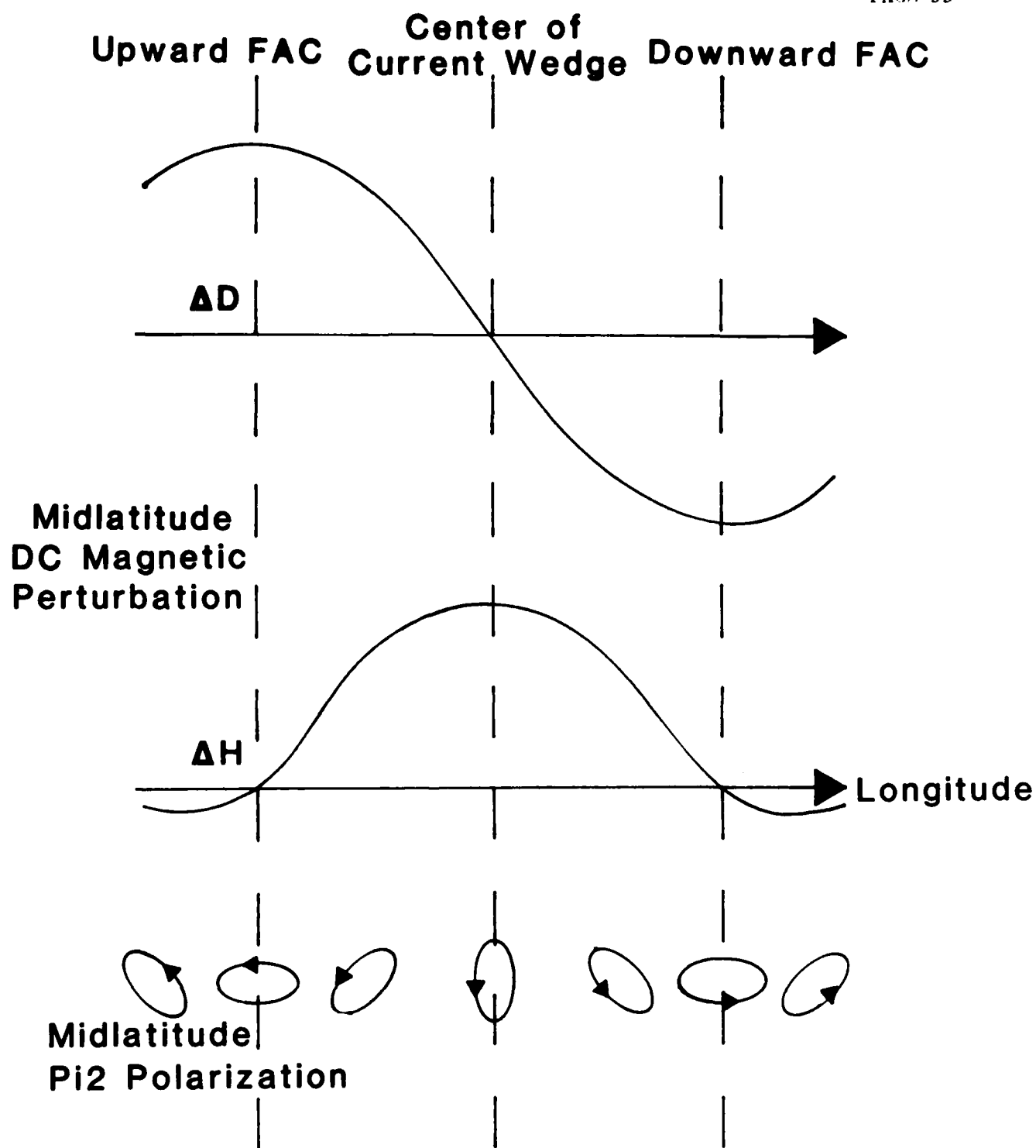
Figure 2: The upper portions show schematically the midlatitude magnetic perturbations caused by the substorm current system shown in figure 1. The D component perturbation is antisymmetric about the center of the current system, being positive to the east and negative to the west of the center. The H component perturbation is positive near the center of the current system and passes through zero near the meridians of the field-aligned currents. The pi2 polarization we have found is represented by the row of ellipses at the bottom of the figure.
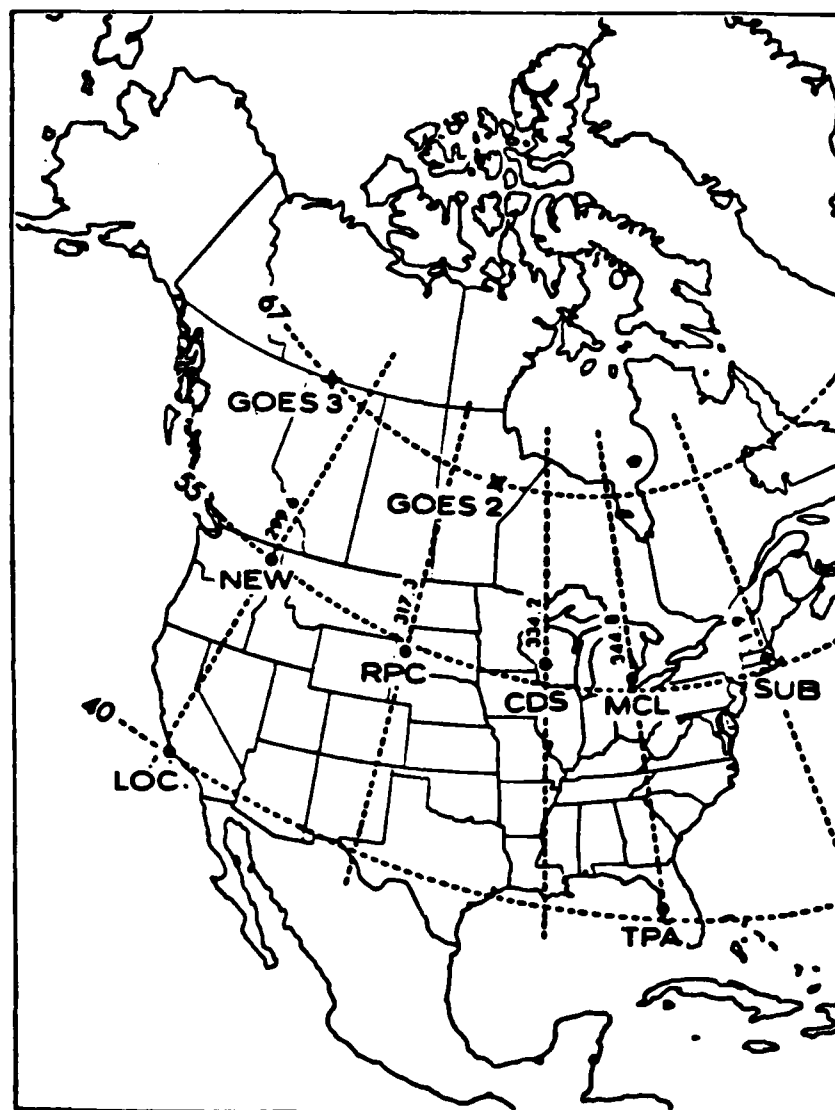
Figure 3: A map showing the locations of the stations of the AFGL Magnetometer Network and their relation to the magnetic conjugate points of the geostationary spacecraft GOES 2 and 3.

14 March1978
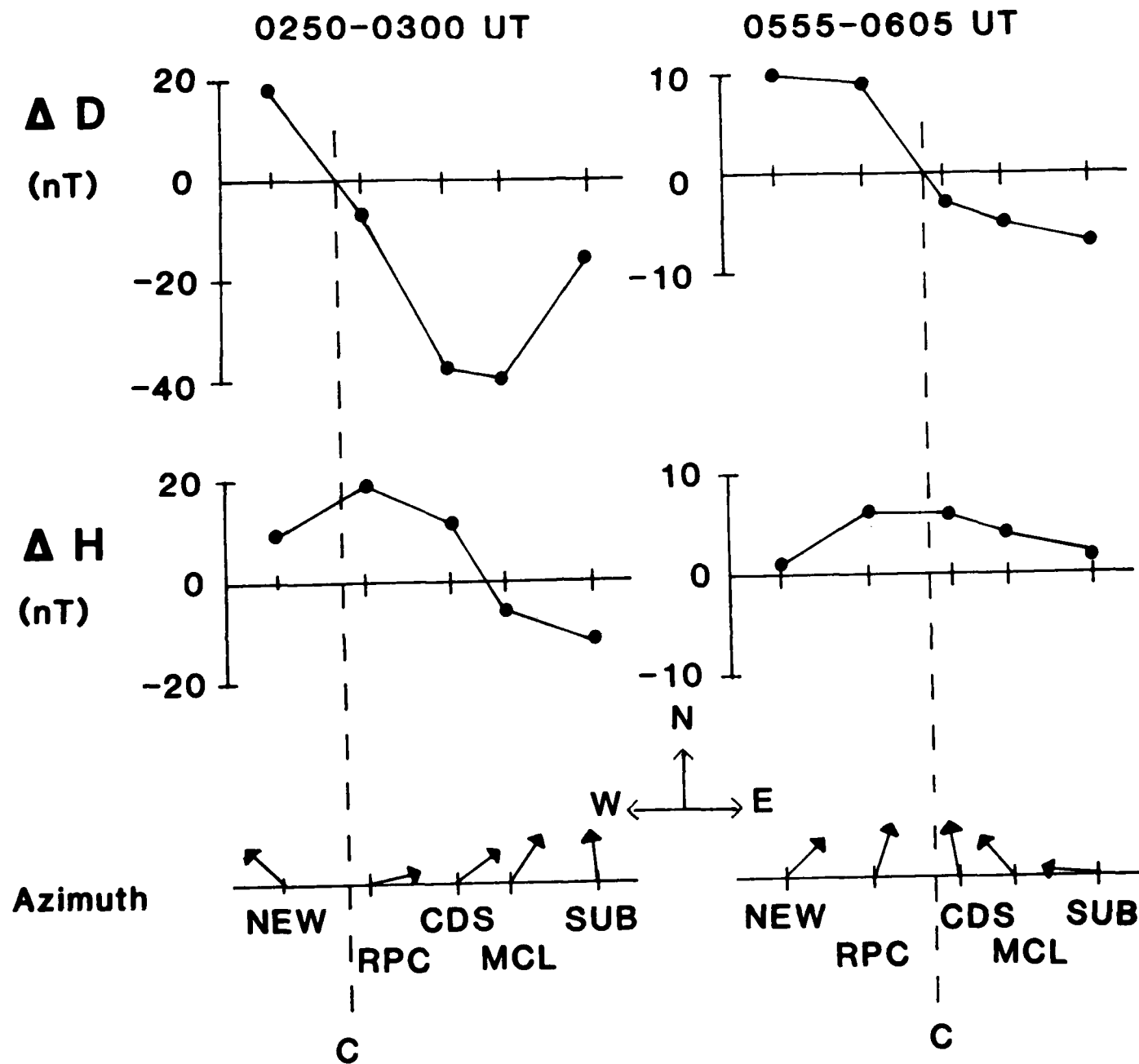
Figure 4: The magnetic bay structure and pi2 polarization azimuths of two pi2 events as observed on the five northern stations of the AFGL Magnetometer Network. The dashed lines marked C are the meridians where ΔD = 0. The event on the right agrees with the schematic picture in figure 2. The polarization and bay patterns are displaced with respect to each other in the event on the left.
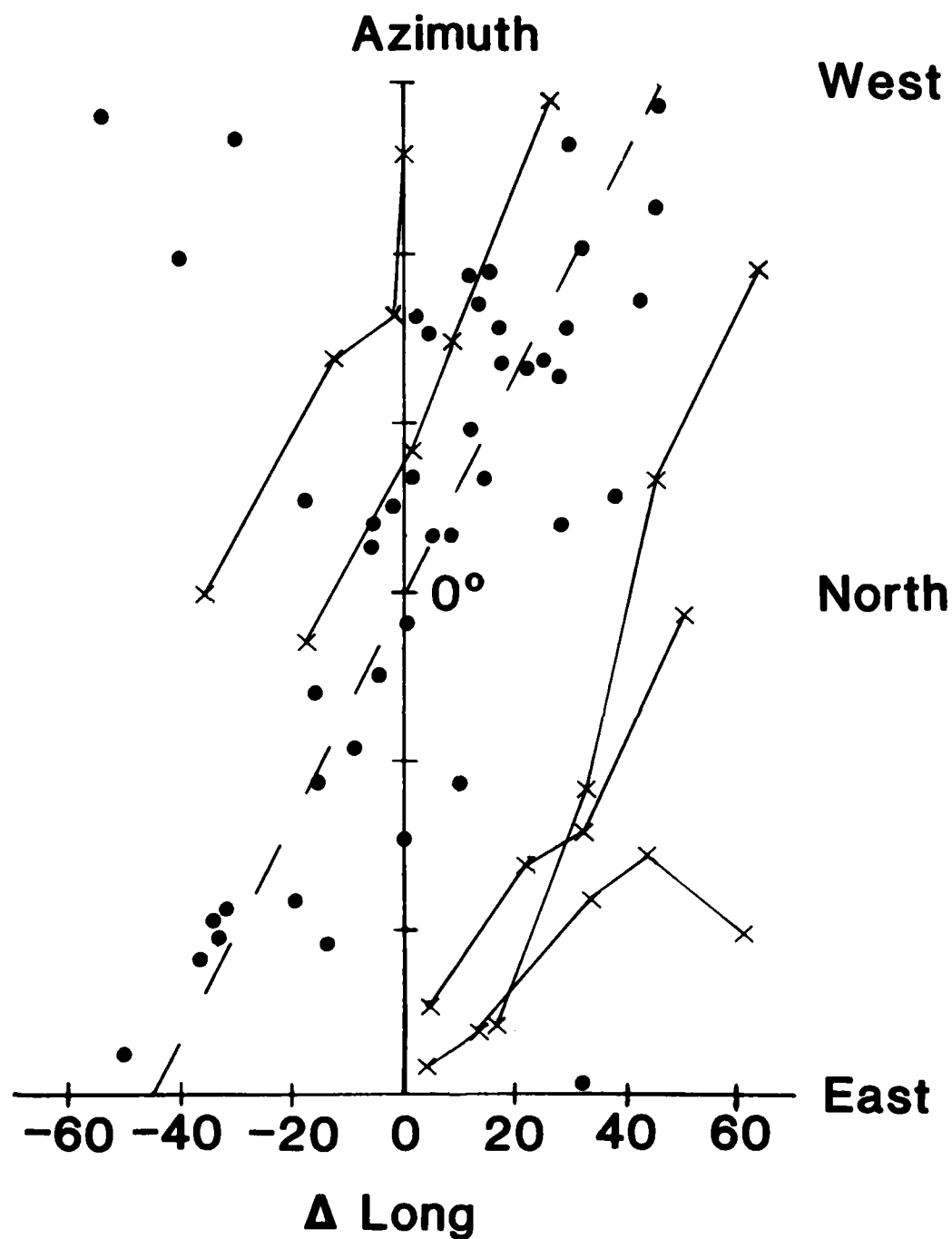
Figure 5: Pi2 polarization azimuth versus the difference in the longitude of the station and the ΔD = 0 meridian for 16 pi2 events observed with the five northern AFGL stations. The dashed line represents the variation expected for a model current system six hours wide and symmetric about the central meridian.
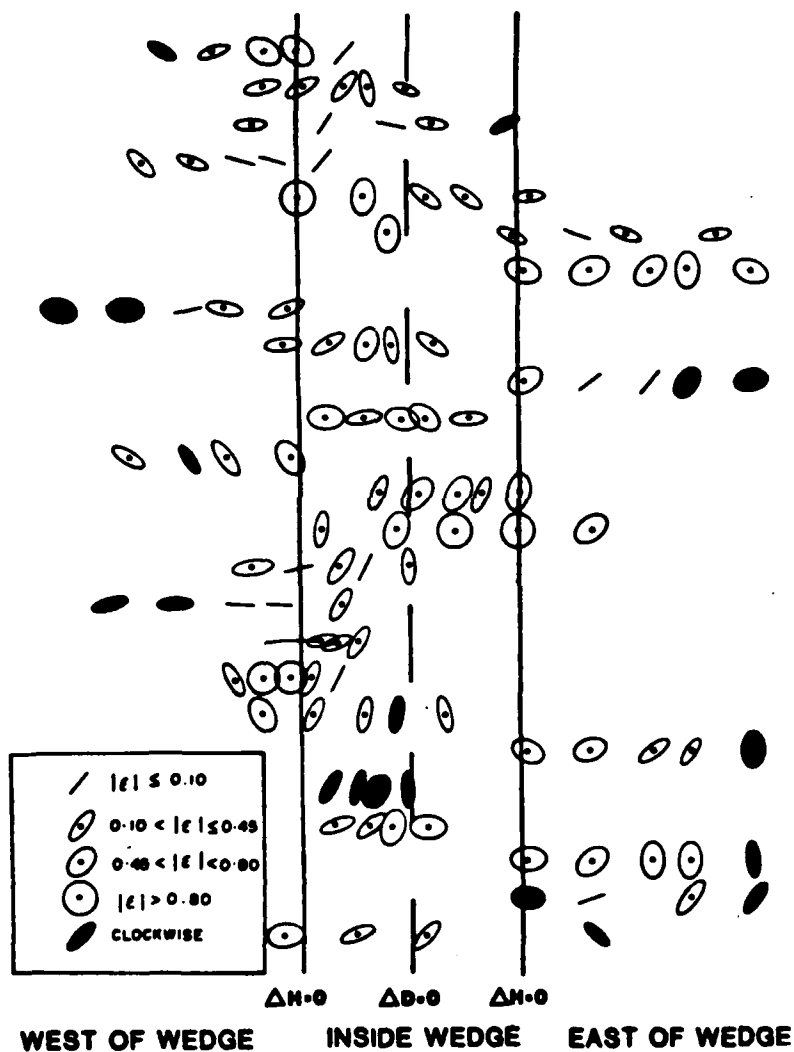
Figure 6: The polarization patterns of 25 pi2 events observed with the AFGL network. The $\Delta H = 0$ and $\Delta D = 0$ meridians are determined from the midlatitude bay structure.
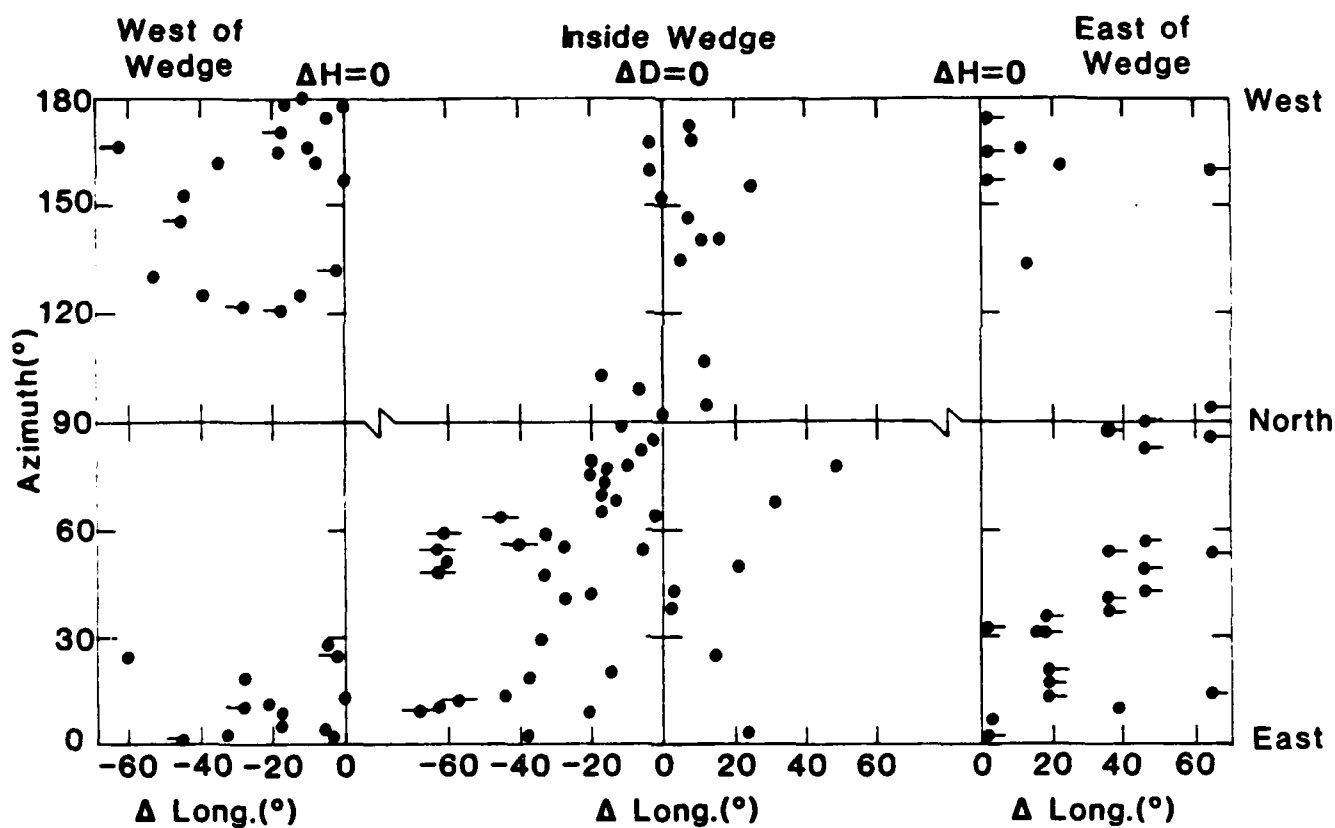
Figure 7: The polarization azimuths seen at the five northern AFGL stations for the 25 pi2 events shown in figure 6. The station longitudes are plotted relative to one of the three meridians defined by $\Delta H = 0$ or $\Delta D = 0$.
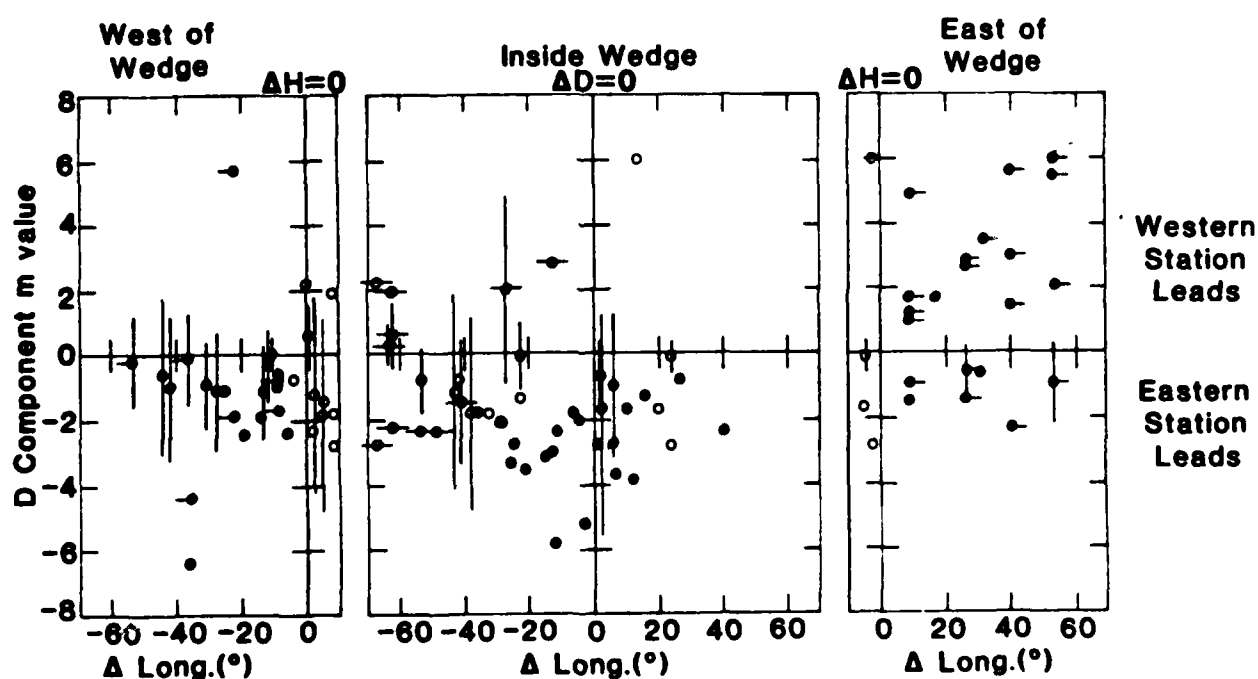
Figure 8: Azimuthal phase differences plotted as angular wave number, m, computed using adjacent pairs of the five northern AFGL stations for the 25 pi2 events shown in figure 6. The points are plotted at the longitude of the midpoint between the stations relative to one of the three meridians defined by $\Delta H = 0$ and $\Delta D = 0$. Points represented by open circles appear on two panels.
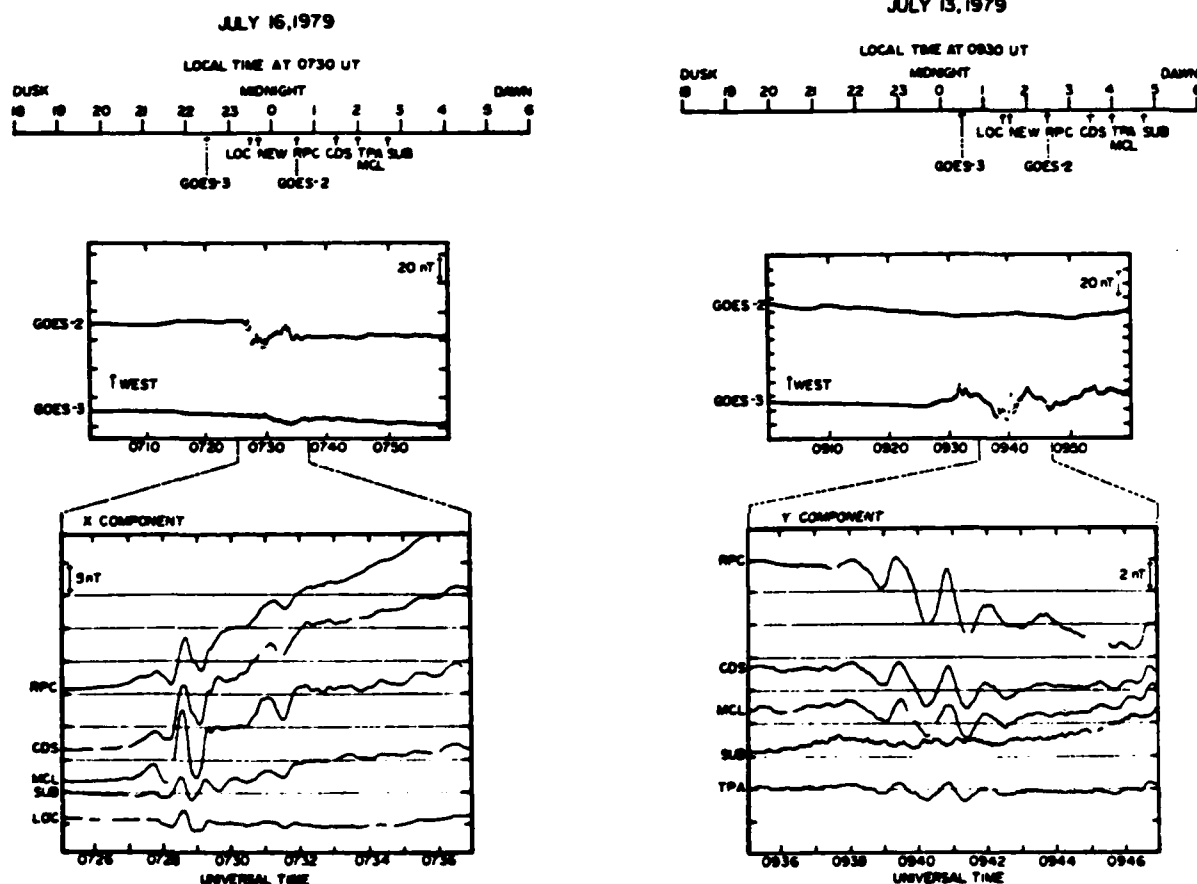
Figure 9: Two pi2 pulsations seen by all the stations of the AFGL Magnetometer Network which were operational (lower panels). The event on the left was accompanied by a pi2 wave burst at GOES 2 but there was no signature at GOES 3 (upper panel). The reverse occured during the event on the right. The scales at the top of the figure show the local times of the spacecraft and ground stations at the time of the events.

Pi 2 OBSERVATION vs K$_p$ JULY 1979 0000-1200UT
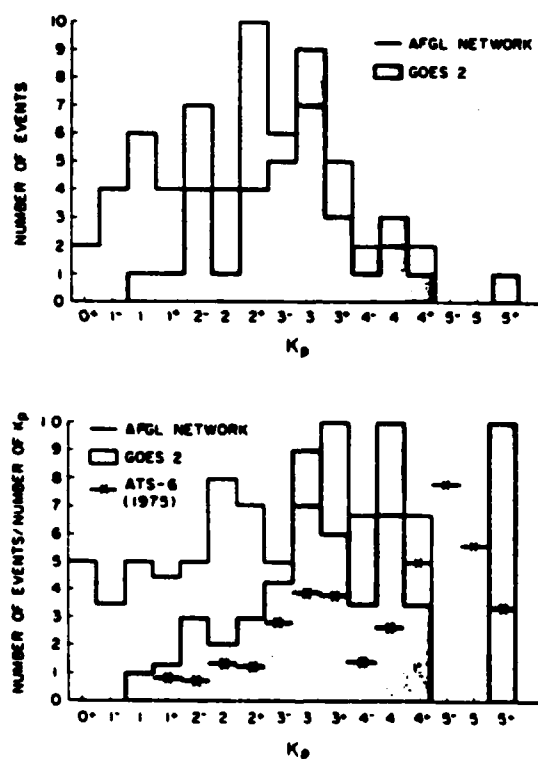
Figure 10: Histograms showing the number of pi2 pulsations observed by the AFGL Magnetometer Network and by GOES 2 during July 1979 versus K$_p$. The upper panel shows the total number of events; the lower panel shows the number of events normalized by the K$_p$ distribution. The lines with a cross show the number of events seen by ATS 6, another geostationary spacecraft, during a different time interval.

LOW Kp   AURORAL OVAL CONTRACTED

GOES

SURFACE WAVE ?
RESONANCE ?

Pi 2 SOURCE ?

GOES
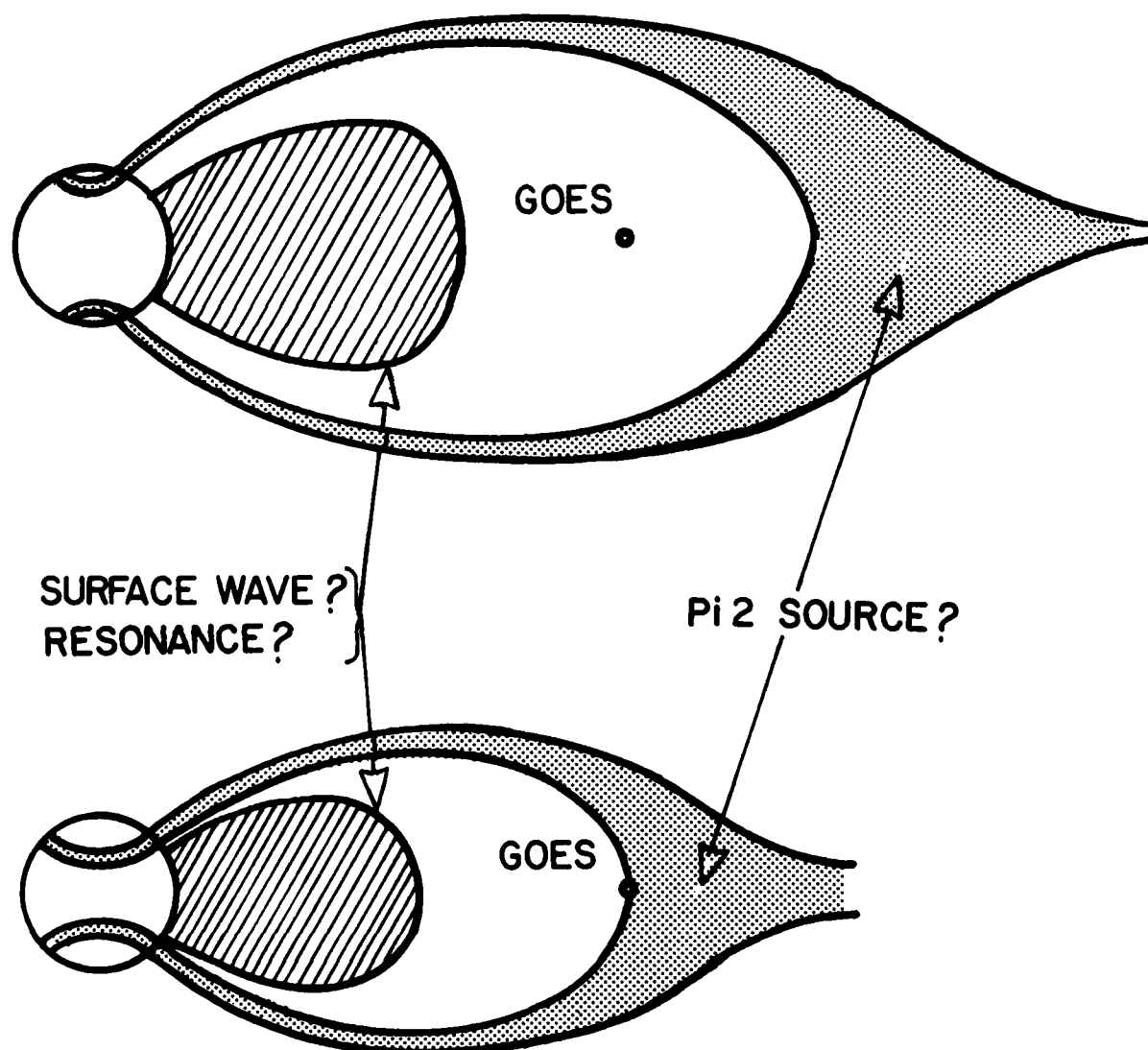
HIGH Kp   AURORAL OVAL EXPANDED

Figure 11:   Schematic illustration of the position of the noon-midnight meridian of the auroral oval, plasma sheet and plasmasphere during times of low and high K_p. Also shown are possible positions of a geostationary GOES spacecraft relative to the plasmasheet, the likely source region of pi2 pulsations.

AFGL MAGNETOMETER NETWORK   July 16, 1979

H Component
10 nT/div

RPC

CDS

MCL

SUB

LOC

D Component
10 nT/div

RPC
CDS
MCL
SUB

LOC
TPA

0715   0725   0735   0745
Universal Time
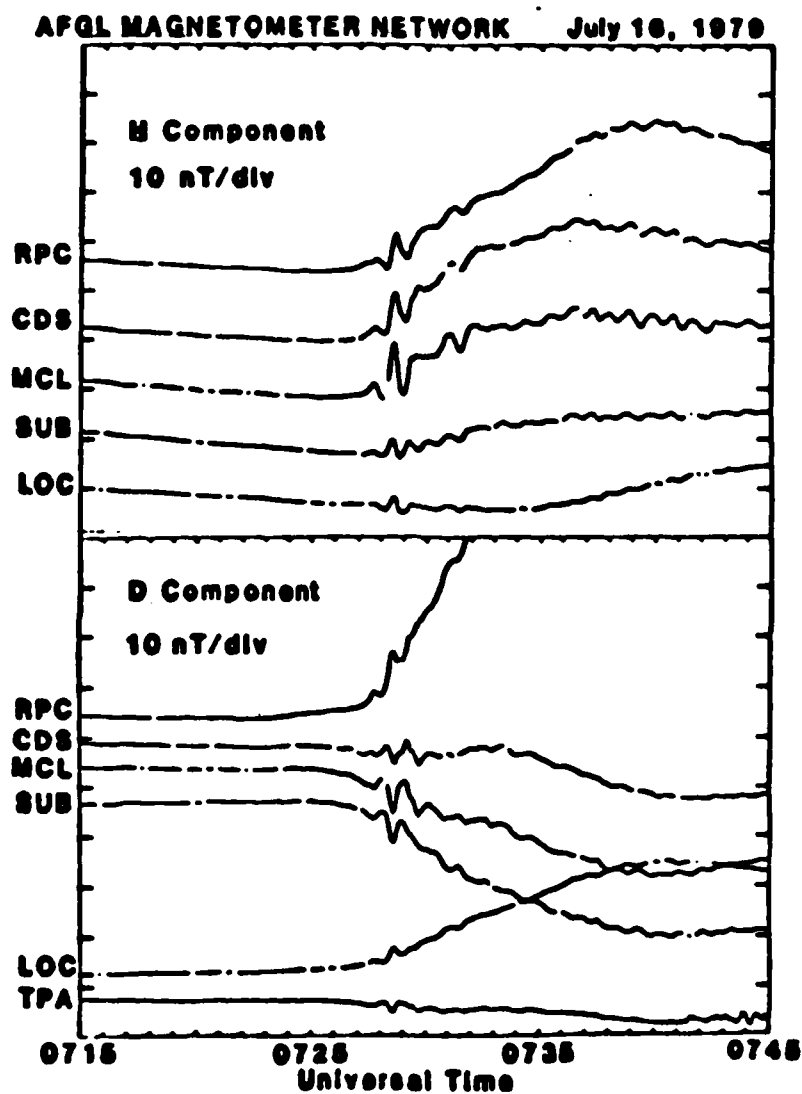
Figure 12:   A pi2 pulsation and magnetic bay observed by the AFGL Network on 16 July 1979.   The D component perturbation changes sign across the Network which means that the substorm current system is centered on a meridian between RPC and CDS.

Figure 13: Hodograms of the pi2 pulsation shown in figure 12. These confirm that the substorm is centered on a meridian between RPC and CDS.

JULY 16 1979

15 nT/div

GOES 2 — BZ

GOES 2 — BY

GOES 2 — BX

GOES 3 — BZ

GOES 3 — BY

GOES 3 — BX

0715   0725   0735   0745

Universal Time
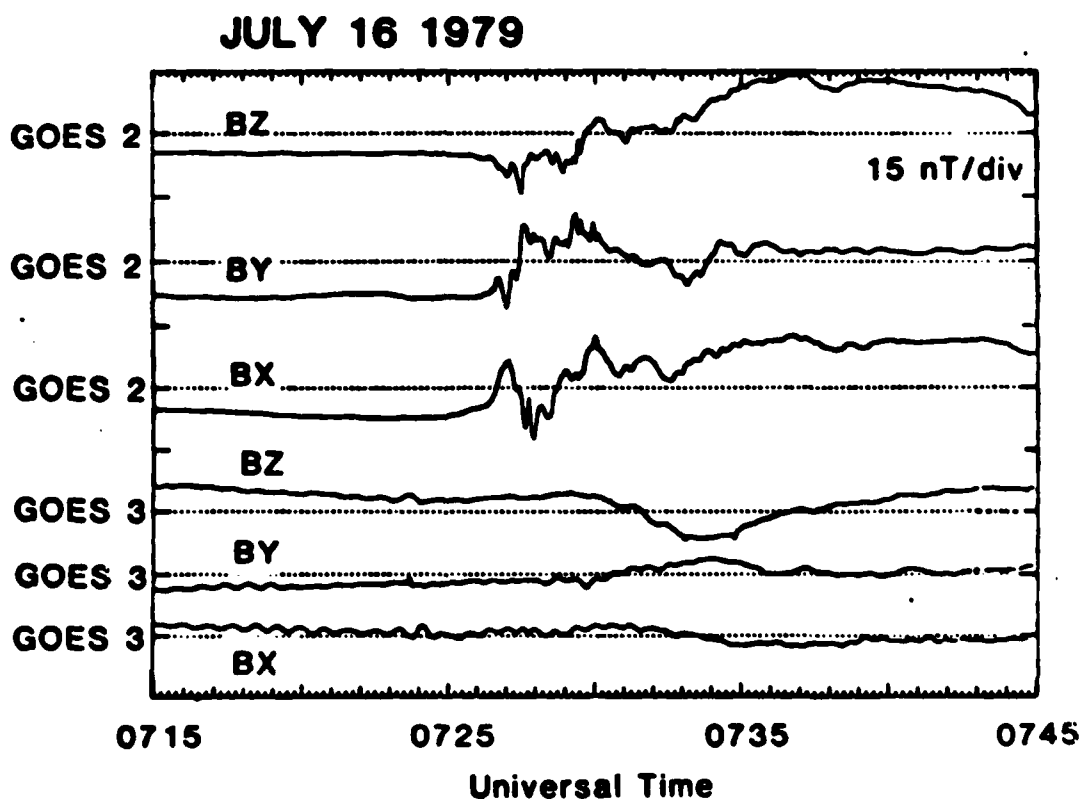
Figure 14:   GOES 2 and 3 magnetometer data for the same time interval as in figure 12.   GOES 2, near the center of the substorm, sees a distinct pi2 wave burst and a field reconfiguration.   GOES 3, outside the substorm current wedge, sees no such signature.
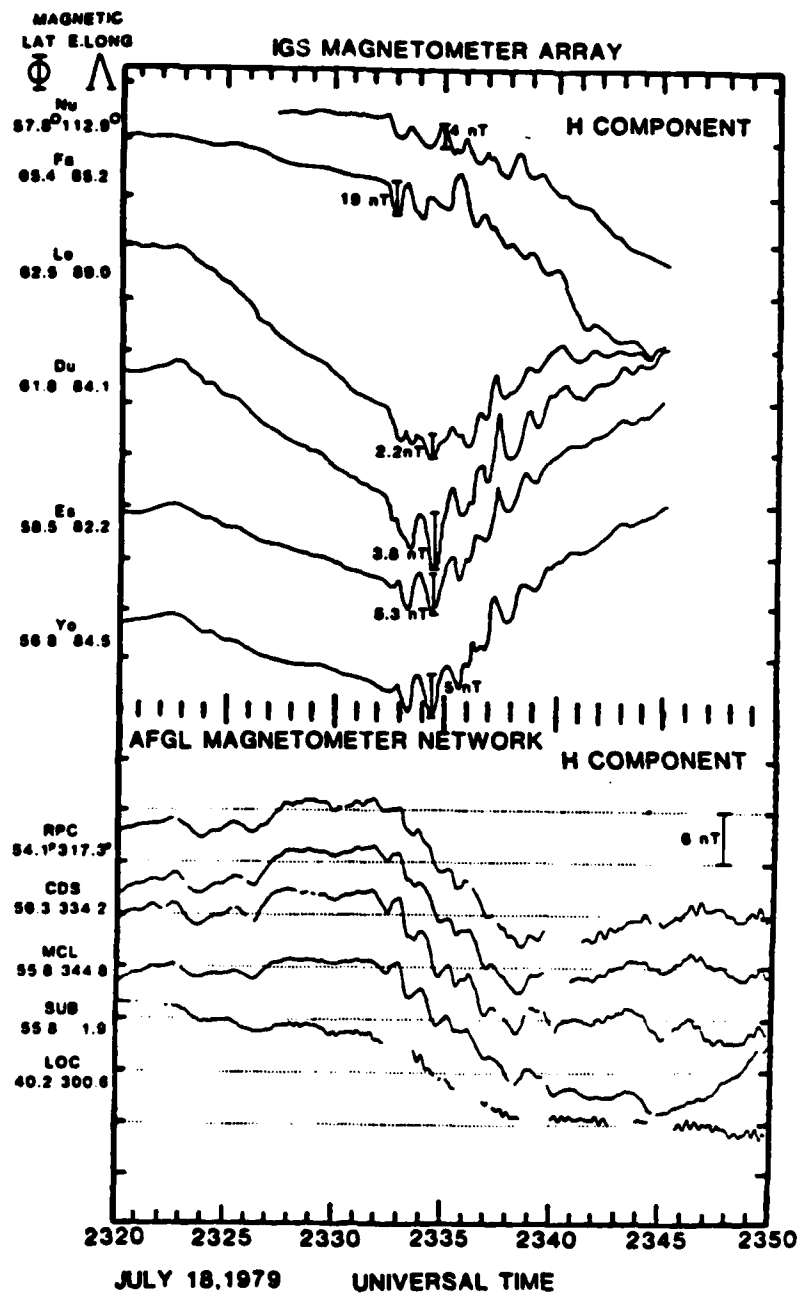
Figure 15: A pi2 pulsation observed simultaneously on the IGS Magnetometer Network in Northern Europe near local midnight (upper portion) and on the AFGL Magnetometer Network in North America in the late afternoon sector.
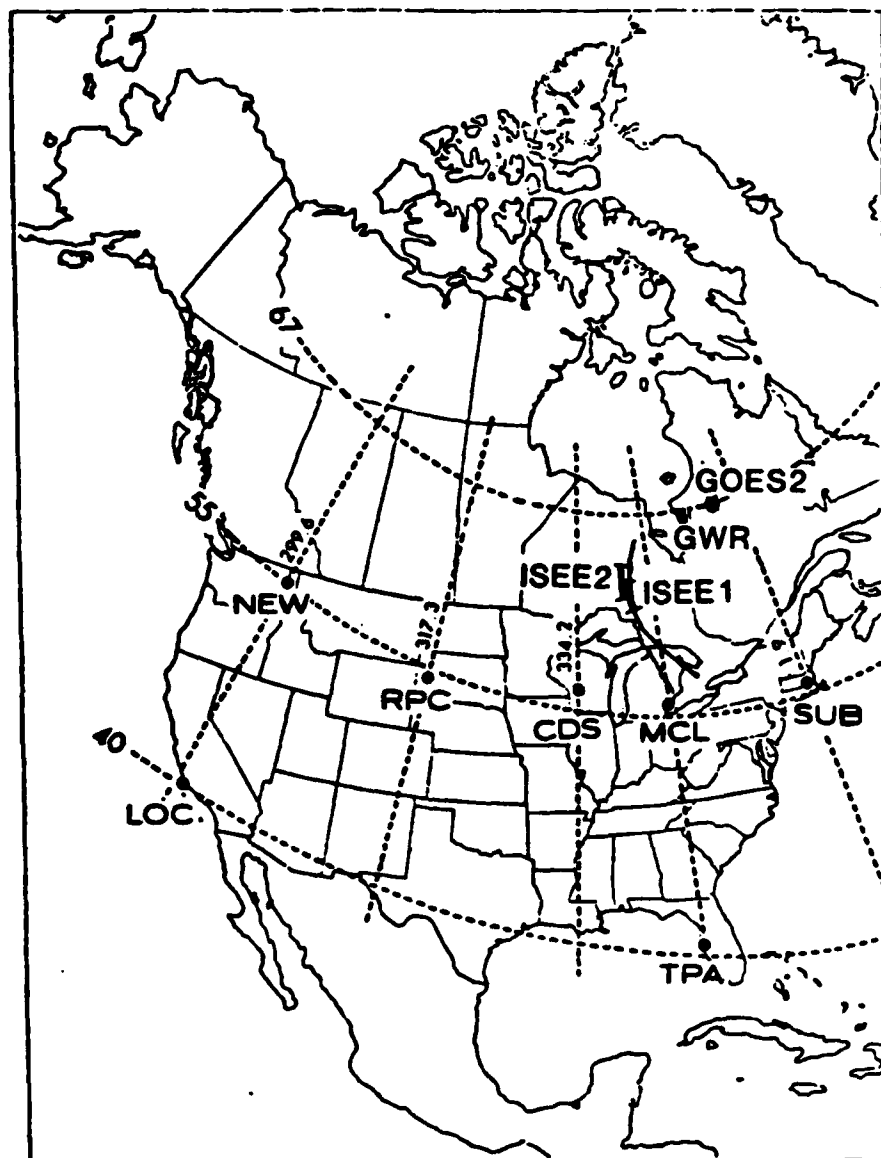
Figure 16: A map showing the locations of the stations of the AFGL Magnetometer Network and Great Whale River as well as the magnetic conjugate points of ISEE 1, ISEE 2, and GOES 2, at the time of the pi2 event on 16 June 1978. The ISEE spacecraft were moving towards the Earth. The part of the ISEE footprint corresponding to the time of the pi2 is drawn as a heavy line.

16 JUNE 1978

ISEE 1 & 2, E & B Fields, Field-aligned Coordinates

AFGL Magnetometer Network
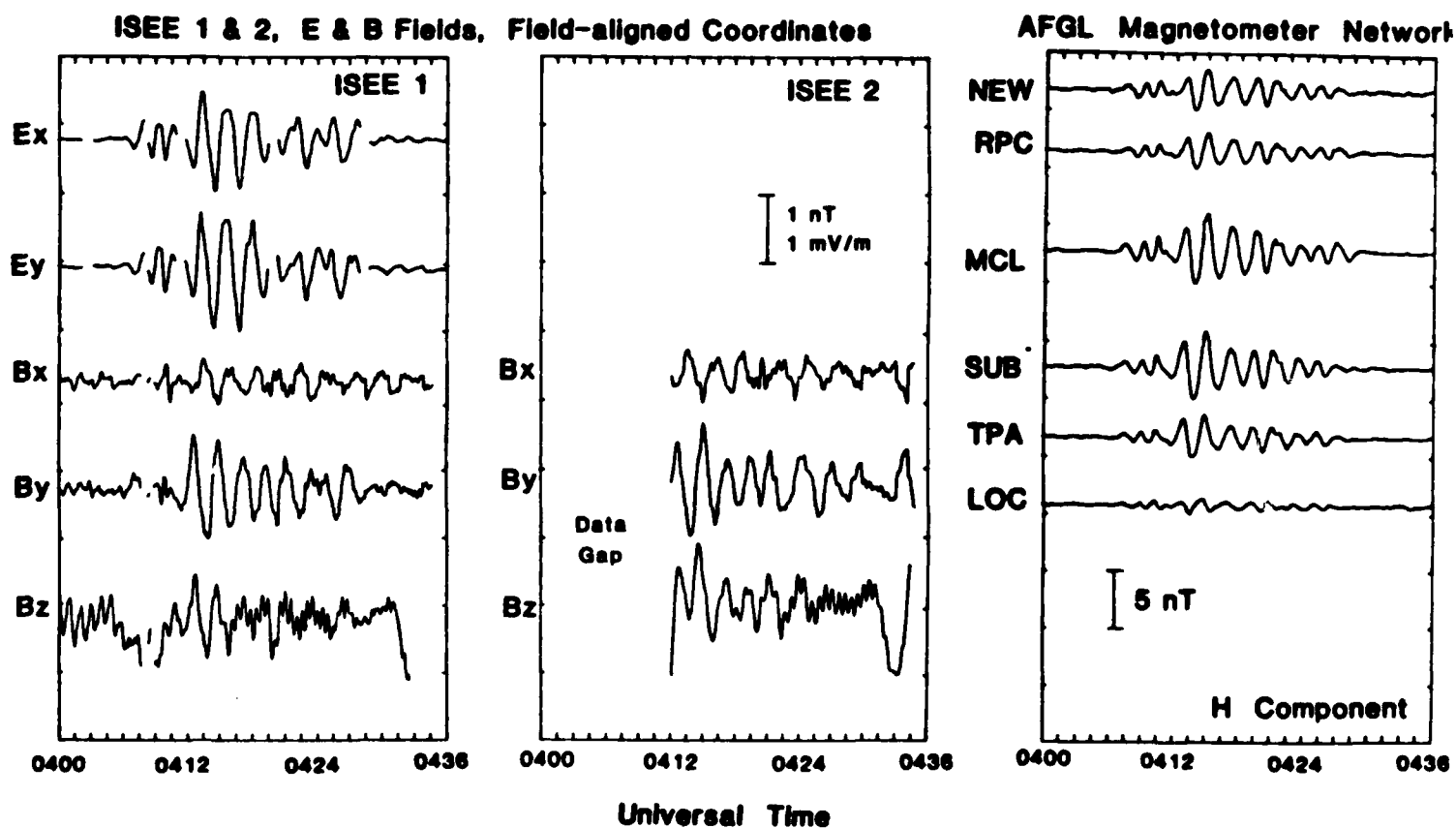
Figure 17: AFGL Magnetometer Network Data, electric and magnetic field data from ISEE 1 and magnetic field data from ISEE 2 showing a pi2 pulsation. The ISEE spacecraft were near L = 5. There is a clear strong correlation between the signature on the ground and in space.

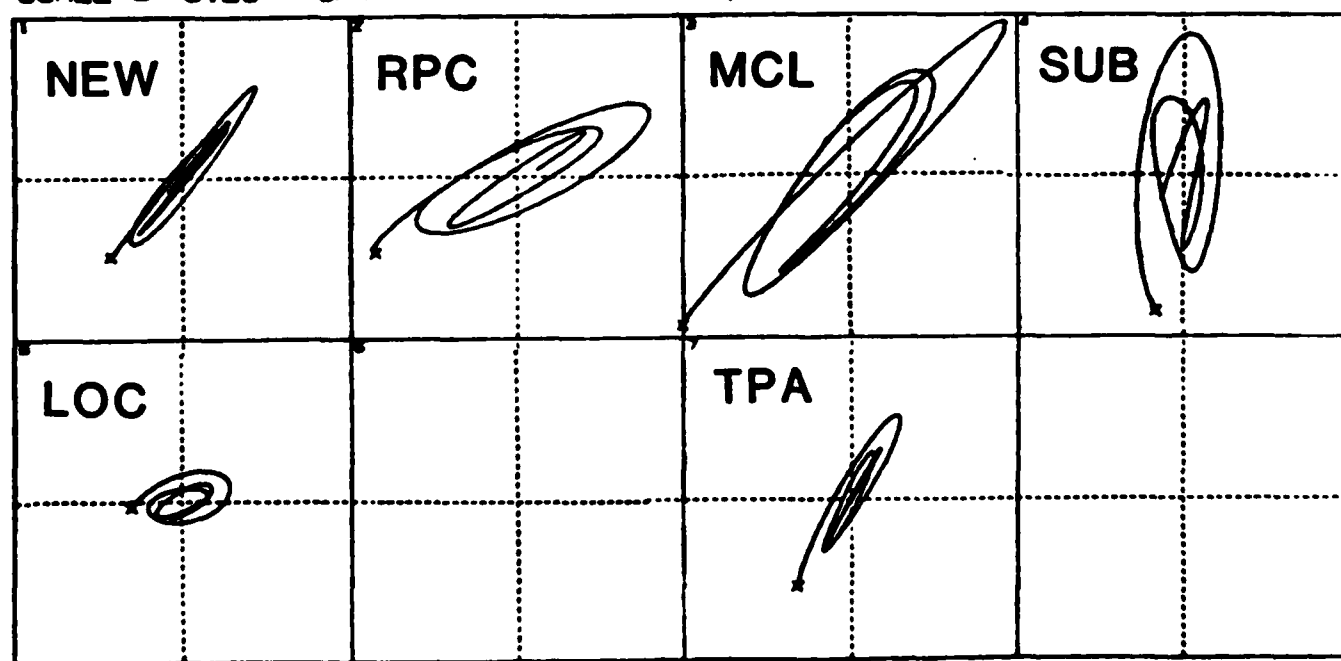# AFGL Magnetometer Network

16 June 1978, 0414-0420 UT

Figure 18: Hodograms of the AFGL Network data for the pi2 shown in Figure 17.
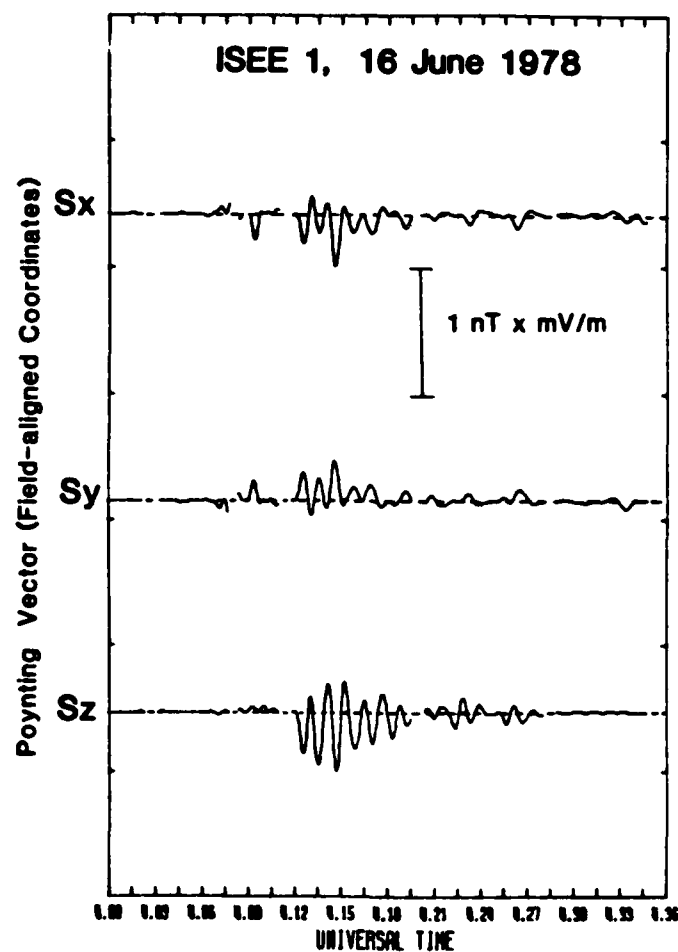The substorm was centered approximately on the SUB meridian.

Figure 19: The Poynting vector computed from the ISEE 1 magnetic and electric field data for the pi2 pulsation shown in figure 17. The vector is in mean-field-aligned coordinates; S_z is the component along the ambient field direction.
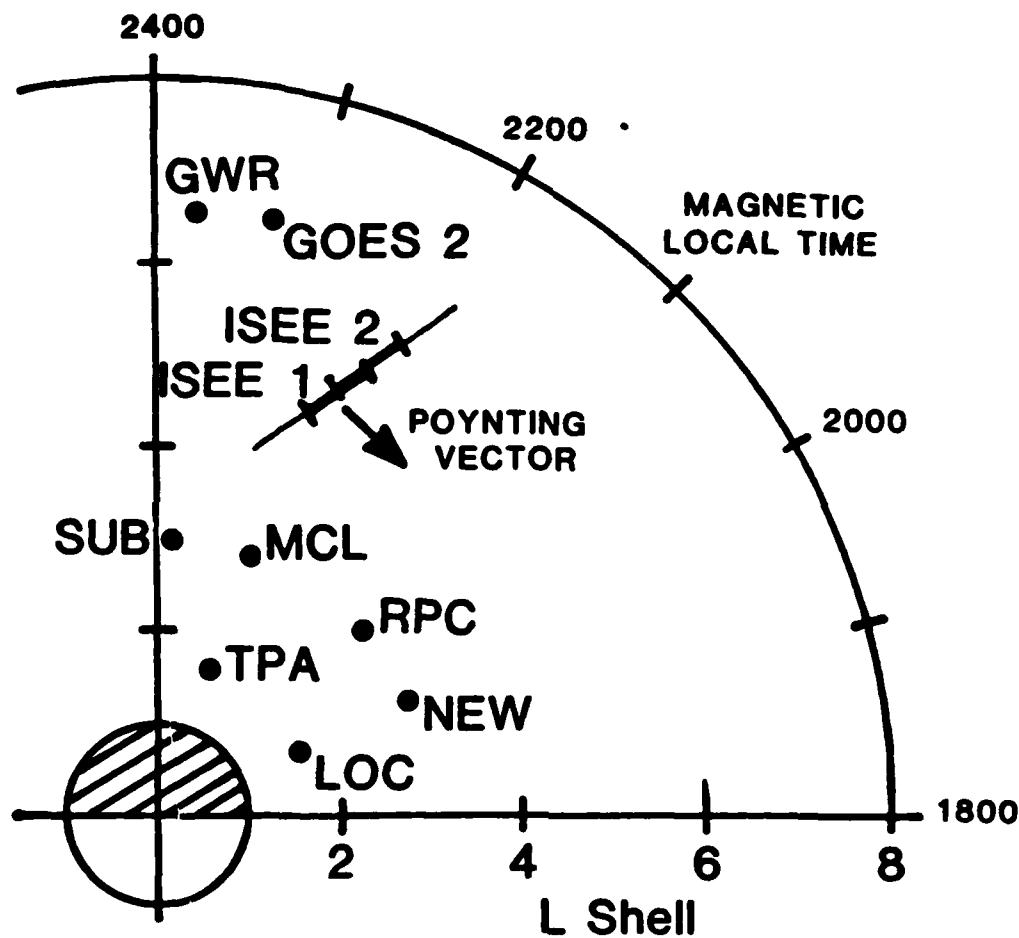
Figure 20: The spacecraft and magnetometer station positions in L shell and Magnetic Local Time. The arrow shows the direction of the net Poynting vector perpendicular to B at ISEE 1.
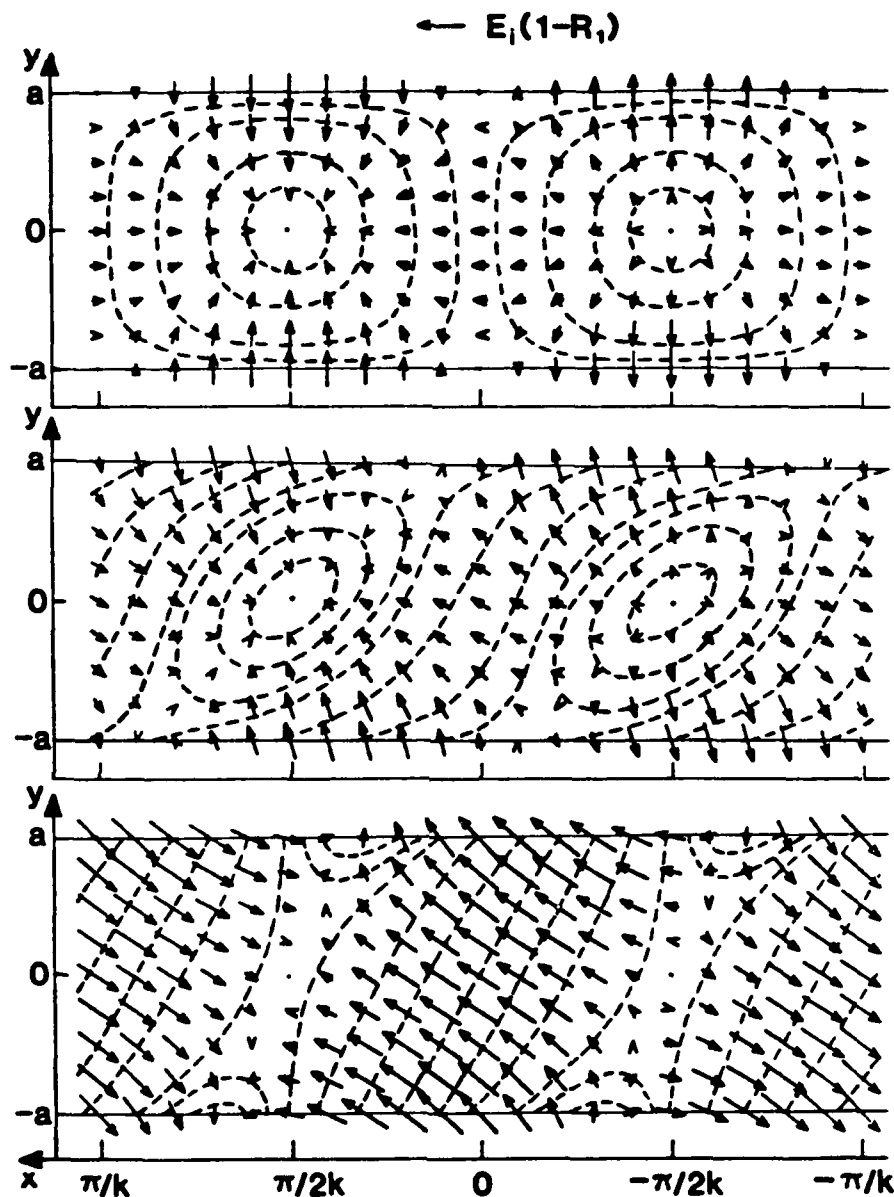
$$\longleftarrow E_i(1-R_1)$$

Figure 21: Three examples of the ionospheric electric field distribution (arrows) and direction of Hall current flow (dashed lines) in a high conductivity strip model of the auroral ionosphere. The incident wave is a plane polarized Alfven wave travelling in the positive x-direction with its electric field polarized in the x-direction. The three panels are for different ratios of integrated Hall to Pedersen conductivity. The single arrow at the top of the figure shows the strength and direction the electric field would have in the case of uniform ionospheric conductivity.
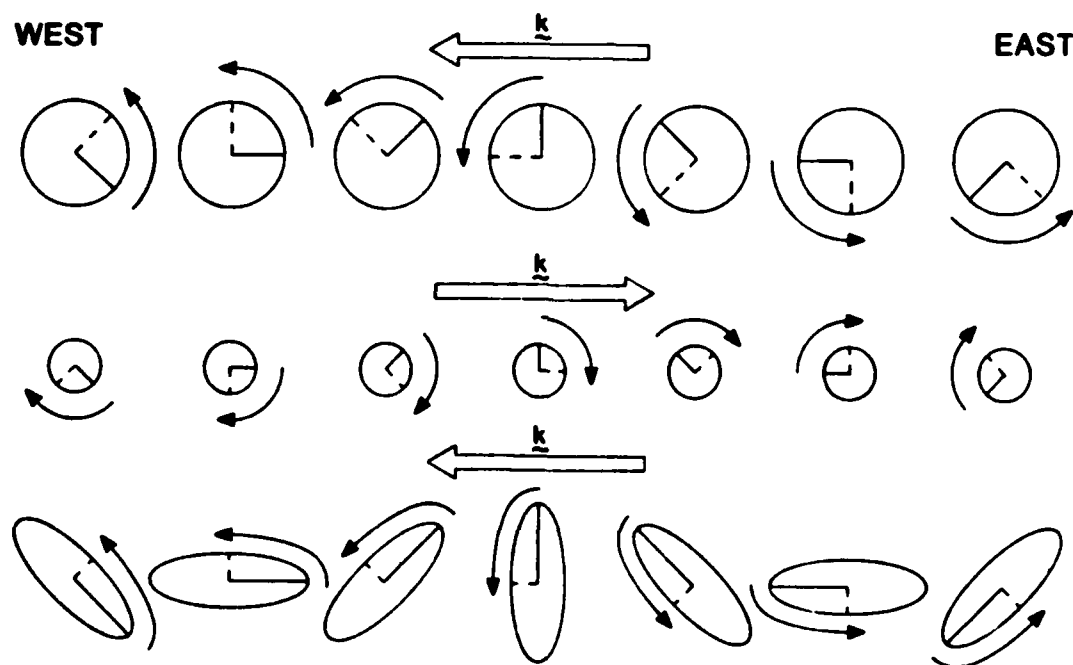
Figure 22: Schematic hodograms of three waves observed at seven observatories in an east-west line. The top row is an anticlockwise circularly polarized, westward-travelling wave. The second row is a clockwise circularly polarized eastward-travelling wave with amplitude half that of the westward travelling wave. The bottom row is obtained by adding the first two rows. The resultant wave is anticlockwise elliptically polarized and has a net westward phase motion. However, the orientation of the ellipse is different at each station; the pattern is similar to pi2 polarization patterns at midlatitudes (cf. figures 4, 6, 13, and 18).

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